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EXPERIMENTAL STUDIES OF TWO IMPORTANT FACTORS UNDERLYING MASCULINE SEXUAL BEHAVIOR: THE NERVOUS SYSTEM AND THE INTERNAL SECRETION OF THE TESTIS

BY CALVIN P. STONE

University of Minnesota

Many contributions to the psychology of sex have come during the past fifty years from the fields of physiology, zoölogy, embryology, anatomy, and pathology. The incorporation of these contributions in the psychology of sex (Moll, '12, Ellis, '13) has given to the latter what harmony with sexual physiology it now possesses.

It has opened the way for experimental study of both the fundamental elements of the reproductive mechanism and the factors by which they are activated and controlled. For this reason it is desirable that psychologists continue to revise and restate the sexual theories as new data appear which throw additional light upon the operation of the sexual responses. In the following paper an attempt has been made to consolidate the literature bearing upon two important factors underlying masculine sexual behavior, namely: the nervous system and the internal secretion of the testis.[1]

THE CENTRAL NERVOUS SYSTEM AS A REGULATOR OF SEXUAL BEHAVIOR IN THE MALE

Early investigators looked upon the central nervous system as the sole activator and regulator of sexual behavior.

[1] In this review all data pertaining to the regulatory influence exercised by the gonad over the growth and maintenance of somatic sexual characteristics are omitted. Comprehensive reviews of these data are given by Bell ('16), Biedl ('13), Marshall ('10), Paton ('13), Vincent ('12), Wheelon ('17), and others listed in the bibliography.

Gall, writing in the first quarter of the nineteenth century, was one of the first to localize the seat of the sexual impulses. He placed it in the cerebellum. This part of the brain was favored because of certain anatomical and clinical observations which had come to his attention. He believed that: (1) The growth of the cerebellum is arrested greatly when animals are castrated at an early age; (2) the cerebellum undergoes marked atrophy following castration of the adult; (3) after semi-castration there follows shrinkage of the contra-lateral hemisphere of the cerebellum; (4) and that a general shrinkage of the cerebellum occurs in senility.

It may be said at the outset, in criticism of Gall's generalizations, that they are not substantiated by subsequent anatomical and experimental evidence. Leuret ('39) compared the gross weights of the encephala and cerebella of 10 stallions and 21 geldings. The percentage weights of the cerebella with respect to the encephala were 11.4 and 13.5. Here an actual reverse of Gall's observation is indicated. Hatai's ('13) tables showing the effects of gonadectomy on the weights of various parts of the central nervous system indicate only slight changes in the gross weight of the central nervous system as a whole following semi- and complete castration of albino rats. Such changes as appeared were proportionately distributed to the parts of the brain and not confined to the cerebellum. No disproportionate loss in the contra-lateral hemispheres of the cerebella following semi-castration were reported. With respect to weight changes occurring in senility in man, Boyd ('61) demonstrated that the changes in gross weights of cerebrum and cerebellum are proportional for advancing ages from adulthood to senility. Thus it is evident that Gall's views are at the present time of little more than historical interest.

In 1873 Golz reported observations on partially decerebrate dogs from which he concluded that the sexual impulses were regulated by a particular part of the cerebral cortex. This view has been strengthened by extensive researches of von Bechterew ('08) who described a cortical region in the dog where the application of electrical stimuli gave rise to

erection of the penis and to ejaculation of semen. Similar findings were reported by Pussep ('02), a student of von Bechterew. Others have been less successful in locating this so-called sexual center in the dog and other animals, yet many writers (Moebius, '00, Kraft Ebbing, '03, Loewenfeld, '11, Orlowski, '09, and others) state or manifest in their writings their belief in its existence.

Certain investigators (Budge, '58, Eckard, '63, and Golz, '98) have hinted at the possibility of a sexual center in the brain-stem. Their chief ground for localizing a sexual center in the brain-stem was the observation that mechanical stimuli applied to the regions of the crura cerebri, the pons, and even the cervical cord, as in execution by hanging, are sometimes followed by the reflex activities of erection and ejaculation.

Not all investigators agree, however, that there is in the cerebral cortex or brain-stem a circumscribed area or center which presides over the sexual functions. Leaders in the opposition to this view are Müller and Dahl ('12). These investigators maintain that the cortex functions in sexual activities only in the same generalized manner found in the vegetative or visceral activities. They believe it plays some rôle, still unknown, in associative learning in connection with sexual activities, but has no special center or nucleus to which this rôle may be attributed. They stress, as others have done, the essential segmental reflex nature of the primary sexual activities involved in erection and ejaculation, which has been clearly demonstrated by the researches of Eckard ('63), Langley ('91), Sherrington ('92), and Langley and Anderson ('96).

No account can be given at the present time which satisfactorily indicates the degree to which the preparatory sexual responses (sexual orientation, seeking movements, courting, etc.) are dependent for their activation and execution upon the integrity of the central nervous system. Experimental work in this field is urgent and is almost certain to yield data of far-reaching importance in outlining the neuro-physiology underlying congenital activities.

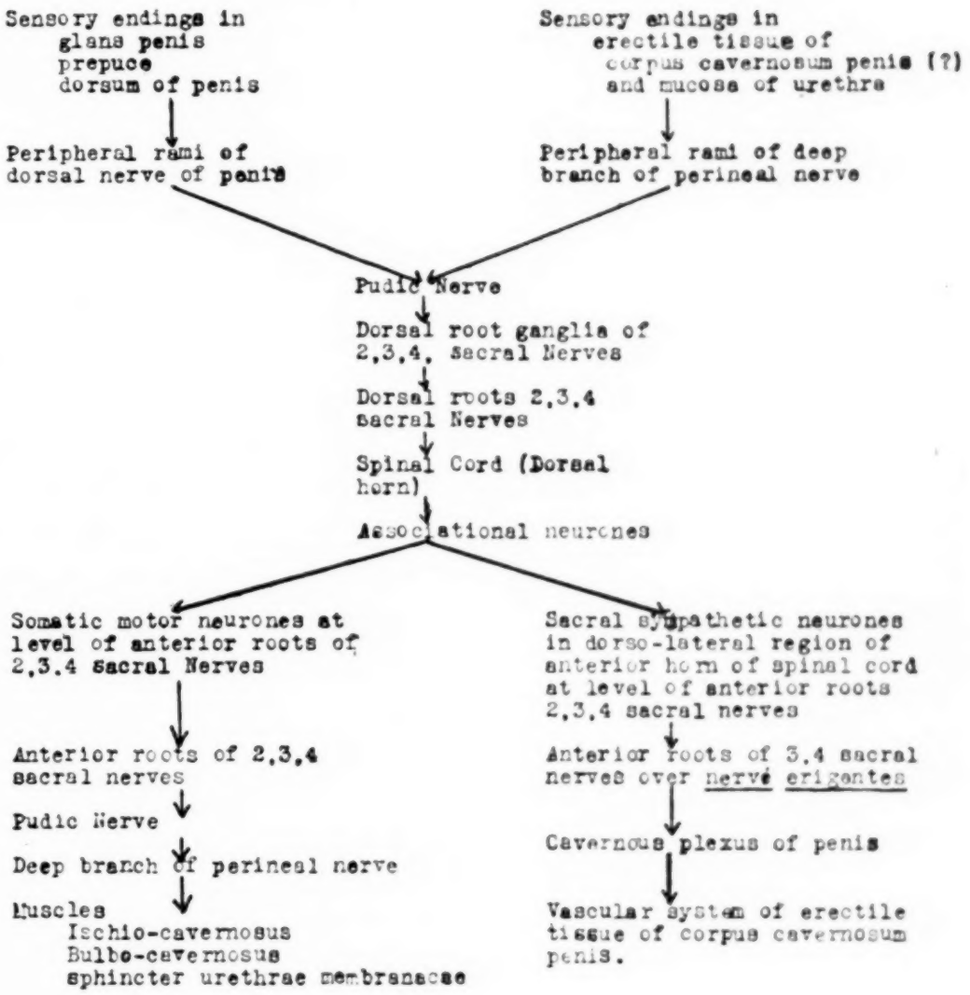
It may be conjectured that a transected cord, although

permitting the activation and execution of the primary sexual reflexes (erection and ejaculation) would greatly alter the preparatory sexual responses in the male because of the general paralysis of the lower extremities such an operation would entail. There is no reason to doubt, however, that sexual activities which are not dependent upon the lower extremities would be executed if not prevented by traumatic effects of the operation. This belief is supported by the results from experimental studies on the female dog whose rôle in the sexual act, although not passive, involves a somewhat lesser degree of bodily movement than that of the male. Golz ('74) reported the case of a bitch with cord transected in the lumbar region. She came into heat, received the male, conceived, delivered, and suckled her young. Sherrington also has described the behavior of a bitch with cord transected in the cervical region, cephalad of the connection between the sympathetic system and the cord, which repeatedly passed through complete oestrual cycles. These findings taken with other observations of similar significance show that the arousal of many of the primary congenital sexual activities in the female are not dependent upon the integrity of the central nervous system. Experiments alone, however, can prove or disprove the conjectures made concerning the male.

A great amount of research has been directed by anatomists and physiologists to the problem of defining reflex pathways concerned with erection and ejaculation. The principal reflex arcs can now be given with a high degree of certainty. In the accompanying diagrams the most direct afferent and efferent limbs of the reflex arcs involved in erection and ejaculation are outlined.[1] Other afferent limbs of reflex arcs leading to erection and possibly ejaculation might be similarly diagrammed, such as: that leading from the seminal vesicles and the prostate to the spinal cord or from the mucosa of the urethra to the cord. Their relative importance in causing erection and ejaculation in the normal copulatory act is not known. There is little doubt, however, that they are subordinate to those outlined below.

[1] Taken chiefly from Müller and Dahl ('12) and Morris's 'Human Anatomy,' fifth edition.

Course of Nervous Impulse Leading to Erection



Course of Nervous Impulse Leading to the Ejaculatory Response

Hormone Regulation of Sexual Activities

No account of sexual behavior based wholly upon neurophysiology has been found adequate to explain the facts brought forward from experimental studies during the past thirty years. Hence new dynamogenic factors underlying sexual activation have been sought. This search has led to investigations in the field of endocrinology with the result that data pertaining to a testicular hormone have been revealed which are of interest to students of behavior.

Berthold ('49) demonstrated for the first time under experimental conditions that the testis regulates the 'sexual instincts' and controls the appearance of the somatic secondary sexual characteristics. Since his time various clinical

and experimental evidences have been brought forward to demonstrate this same fact and to indicate the manner in which its influence is manifested. Practically all point to an endocrine function of the testis. Several lines of research have contributed evidence for this belief; of these the most important are: (1) Total castration; (2) castration followed by testicular transplantation; and (3) injection of testicular extracts or tissue. It will be of interest to consider the evidence derived from each of these lines of research.

Total Castration

Many general facts concerning the alterations in behavior following castration have long been known, yet experimental studies have revealed facts that seldom come to the attention of the casual observer.

(*a*) *Castration of Insects.*—It is of considerable interest and importance to note that the effects commonly seen following castration of the higher vertebrates do not appear in some of the invertebrates upon which carefully controlled experiments have been performed. In fact, there is little conclusive evidence that a dependent relationship exists between the secondary sexual characters and the gonads in any of the phyla lower than the cordates. That no such dependent relationship does exist cannot be stated with definiteness, however, because only a relatively small number of species of animals below the vertebrates have been examined. The most comprehensive and conclusive studies have been confined to the insects.

Oudemanns ('99) removed the gonads from both male and female caterpillars of the gypsy moth (*Ocneria dispar*) before the last and next to the last moults. About 30 animals survived the operation and produced moths. Observation of these animals revealed no alterations in their sexual behavior. The males copulated and the females stripped the hairs from their abdomens, an act normally done in ovipositing.

Kellogg ('04) castrated silkworm caterpillars after the second, third, and fourth moults. No alterations in the sexual behavior followed the operation. Adult moths were

dissected after observations were completed to assure the experimenter that the gonads had been completely destroyed.

From a comprehensive study on castrated crickets involving both field observations and observations in a terrarium Regen ('09) reports that sexual behavior in gonadectomized crickets was unaltered. He finds that the males chirped in a lively and shrill manner; they did the usual amount of stridulation to entice the females, and upon the latter's approach they attempted to attach their spermatophores as is the custom of normal males under similar circumstances. Normal females did not discriminate against castrated males. Castrated females showed no aberrations from the behavior of normal females. Adult crickets under observation were later dissected to assure the experimenter that the castrations were complete.

(*b*) *Castration of Vertebrates.*—Castration produces profound changes in the somatic secondary sexual characters and the sexual behavior of vertebrates, as every one knows from his observations on domestic animals. Certain aspects of these changes have proved to be of sufficient theoretical and practical importance to justify their study under carefully controlled experimental conditions. Through these studies many interesting facts have been brought out which are usually overlooked in the routine castration of domestic animals.

Practically all observers agree that castration of vertebrates in early infancy results in total or almost complete suppression of all sexual responses (Scheidenmühl, '83, Steinach, '94, Griffith, '89, Wallace, '07, Sand, '18, Moore, '19, Stone, '21). Castration after early infancy and up to or including the age of puberty causes changes in activity which are determined in large measure by the physiological age of the animal, but which vary considerably according to the species. Pézard ('20) states that the sexual responses are eliminated from the cockerel's repertoire of activities almost immediately upon castration even in the sexually experienced adult. Steinach reports that white rats (normally sexually mature at from 70 to 85 days) when castrated at 45 days of age showed

slight signs of sexual inclination manifested by attentions to females in heat which were somewhat more aggressive than those shown in rats castrated at much earlier ages. Observations carried on by the author tend, in general, to confirm the observations of Steinach.

After castration of white rats 60 or more days of age definite sexual aggression has been observed to occur with a fair degree of regularity for several weeks following the time of castration. Those castrated after they have attained sexual maturity and have had sexual experience are capable of copulating with the usual vigor for a variable length of time thereafter. Steinach ('94) observed that the rat may retain copulatory ability for one year after castration (1 case). Similar retention for variable periods of time has been observed in man and domestic animals castrated in adult life. Although reliable statistical data on subsequent retention of copulatory ability in representative cases of man and laboratory animals are not available, it is generally understood that potency and sexual inclinations gradually weaken and eventually disappear.

The elimination and suppression of sexual behavior in young and adult castrates has been variously explained. The most fundamental explanations have been based on neurological or autocoid evidence.

A typical statement of the neurological explanation is that of Cunningham ('00) which has recently been discarded by this author in favor of the endocrine explanation. He calls attention to the fact that with the ablation of the gonads the peripheral nervous connections to the testes are destroyed. Thus the animal is deprived of the afferent impulses normally arising from the testis, its immediate appendages, and sheaths which, in the normal state of gonadal activity, are distended by secretory products. With the principal afferent limb of the reflex arc broken, the entire sexual mechanism is thrown out of working order. This causes not only the profound changes in behavior that follow castration but also the changes that occur in the somatic secondary sexual characters. Such an hypothesis is untenable in the light of experimental

data arising from the ingrafting of testicular tissue following castration.

Closely associated with the neurological explanation is one which concerns the accessory glands of the reproductive tract. There is a general belief, especially among clinical observers, that the 'sexual desires' are ofttimes aroused and augmented by afferent impulses arising from the seminal vesicles, the prostate gland, and such other glands as are found in the reproductive tract of animals when these glands become filled with secretions and their walls distended. The importance of this conjecture is greatly minimized by the results obtained through the ablation of these glands. Various investigators (for a critical review of this work see Marshall's 'Physiology of Reproduction') have removed both the prostate and the seminal vesicles from animals without loss, diminution, or modification of sexual ardor. Hence it seems quite improbable that they are important factors in the arousal of sexual activity.

A third explanation, one which has received the most experimental support, is based on the assumption that the testis elaborates an internal secretion which, through its chemical influence on the nervous system and the general bodily metabolism, predisposes the animal to orient with respect to animals of the opposite sex and to carry out such further sexual responses as will eventually lead to the consummation of the reproductive act. The persistence of sexual behavior after castration is explained on the assumption that libidinous substances are retained in the blood for a variable period of time (Steinach, '94). Their eventual elimination from the blood stream causes the suppression of sexual responses.

Transplantation of Testis

To Berthold ('49) we owe credit for first demonstrating that the transplanted testes of fowls will maintain the somatic secondary sexual characters and prevent the regression of the sexual behavior to that of the capon. Having castrated four normal cockerels, Berthold transplanted the excised testes

into their bodies. The transplants became established in their new positions and functioned in such a manner as to completely offset the regressive changes in the behavior ordinarily following caponization. From the relationship observed to exist between the presence of the male gonads and the maintenance of somatic and 'psychic' characters of the fowl, Berthold formulated and stated his theory that the gonads elaborate an internal secretion, which, circulating in the blood stream, exercises a regulatory influence over the growth of the somatic sexual characters and the 'sexual instincts.' Since his time the transplantation experiment has been repeated upon both the lower and higher animals.

Nussbaum ('95) demonstrated that the vernal rutting behavior of the frog does not appear in gonadectomized males. If, however, upon the removal of the gonads, a small bit of the testis was grafted into the body of the frog no alteration in the usual rutting behavior was found to appear.

Work with birds has revealed very striking alterations in the somatic characters upon transplantation of the gonads following castration. Testicular transplants in the male offset completely the usual changes following upon castration (Foges, '02, Loewig, '03, Pézard, '20). Transplantation of the male gonad into the gonadectomized female causes, generally speaking, but not without exception, an alteration of the sexual behavior of the female in the direction of the male. Just how completely this is done has never been accurately ascertained. In the literature one finds fragmentary notes, remarks, and sweeping generalizations based upon rather uncritical observations which would seem to indicate that all the responses of the female are masculinized. Shattock and Seligmann ('06) reported several cases of hermaphroditic fowls that exhibited masculine behavior. The domestic hen and the female duck were observed to 'tread' other hens and in other ways (fighting, vocalizations, aggressiveness) to show that their behavior had become altered in the direction of masculinity.

Certainly the field is virgin for the student of animal behavior interested in making a detailed analysis of these

alterations in behavior brought about by the use of gonadal transplants or injections. Until such has been done the evaluation of incidental or fragmentary notes, now in the literature on behavior of fowls following heteroplastic transplants, had best be delayed.

Transplantation of the testis into castrated mammals has been rather extensively studied. Steinach ('10, '12, '13) working with white rats and guinea pigs has demonstrated that the presence of testicular grafts offsets completely the appearance of the eunuchoid changes in the accessory reproductive glands and maintains the sexual responses. Similar findings have been reported by Sand ('18), Moore ('19) and others for rats and guinea pigs; by Wheelon and Shipley ('16) for dogs; by Lydsden ('17) and others for man.

In this laboratory observations have been made on white rats for the purpose of determining whether any noticeable effects upon the copulatory pattern might follow in cases where copulatory ability was maintained by grafted tissue. Detailed observations on three such animals revealed no alterations whatever.

Apparently there is no special part of the body wherein the grafted tissue must be lodged. A muscle or part of the body which offers an abundant blood supply is satisfactory. Most frequently grafts are made in the anterior belly wall, but scrotal and renal grafts thrive equally well and sometimes better because of the superior blood supply that may be established. In the scrotal grafts it is sometimes possible to so connect the grafted testis with the spermatic vessels as to give it the normal blood supply. The better the blood supply established, the greater will be the probability that the grafted tissue will live in its new position and function in a manner that serves as a substitute for the eliminated testis in maintaining the secondary characters and sexual behavior.

Testicular Injections

The report of Brown-Séquard upon the beneficial effects arising from subcutaneous injections of testicular extracts into his own body is the first important account of the dyna-

mogenic effects following immediately upon the administration of testicular juices or tissue. This experiment was conducted to test his belief that general debility marking the onset of senility can be largely offset through the use of orchitic extracts from animals. Ten injections of aqueous extracts from the testes of a dog and guinea pigs were made. The first five injections were of the dog's testis, administered between May 15 and May 18 inclusive. The last five of the guinea pigs were given on May 24, 29, 30 and June 4. The effects as described from his own observations were as follows:

> I am seventy-two years old. My general strength, which has been considerable, has notably and gradually diminished during the last ten or twelve years. Before May 15th last, I was so weak that I was always compelled to sit down after half an hour's work in the laboratory. Even when I remained seated all the time, or almost all the time, in the laboratory, I used to come out of it quite exhausted after three or four hours' experimental labor, and sometimes after only two hours. For many years, on returning home in a carriage by six o'clock after several hours passed in the laboratory, I was so extremely tired that I invariably had to go to bed after having hastily taken a very small amount of food. Very frequently the exhaustion was so great that although extremely sleepy, I could not for hours go to sleep, and I only slept very little, waking up exceedingly tired.
>
> The day after the first subcutaneous injection, and still more after the two succeeding ones, a radical change took place in me, and I had ample reason to say and to write that I had regained at least all the strength I possessed a good many years ago. Considerable laboratory work hardly tired me. To the great astonishment of my two principal assistants, Dr. D'Arsonval and Henocque, and other persons, I was able to make experiments for several hours while standing up, feeling no need whatever to sit down. Still more; one day (the 23d of May) after three hours and a quarter of hard experimental labor in the standing attitude, I went home so little tired that after dinner I was able to go to work and to write for an hour and a half a part of a paper on a difficult subject. For more than twenty years I had never been able to do as much. From a natural impetuosity, and also to avoid losing time, I had, till I was sixty years old, the habit of ascending and descending stairs so rapidly that my movements were rather those of running than of walking. This had gradually changed, and I had come to move slowly up staircases. After the second injection I found that I had fully regained my old powers, and returned to my previous habits in that respect.

In addition to these observations he reports that his limbs as tested by a dynamometer showed marked increase in strength; that the powers of the spinal cord over the bladder as manifested by the relative lengths of jets of urine ejected before and after the injection were greatly augmented; that his powers of defecation returned to a state of vigor found only in presenile life; and that a greater facility

of doing routine labor of an intellectual type became manifest. The good effects of the injections were of only short duration, he observes. After about four weeks there was a complete return of the old-time lassitude, weakness and general debility.

Little merit has been attached to the results described in the foregoing experiment because inadequate controls were introduced to insure that the effects were not due to auto-suggestion rather than to a testicular hormone. Aware of the inadequacy of his controls, yet firm in his conviction that the observed effects were really produced by the injected substance rather than through suggestion, Brown-Séquard became instrumental in securing similar results on other aged men under experiments which were less equivocal as to the causal factors underlying the effects. One of his colleagues, Dr. Variot, repeated the experiment on three elderly men of the ages fifty-four, fifty-six and sixty-eight years. These individuals were ignorant men who knew nothing of the scientific side of the treatment. No pertinent suggestion was made to them as to the effects to be expected. The observed result on each of these men were much the same as those of Brown-Séquard. Variot, in order to guard against effects produced by suggestion, sought to further control his experiment. He employed words of encouragement to two other patients for the purpose of informing them of effects they might expect from his treatment. This time he injected pure water instead of the testicular juices. No beneficial effects whatever followed these injections. Thus a fairly satisfactory check upon the original experiment of Brown-Séquard was obtained.

Brainard ('89) made injections of the fluid expressed from the ductus deferens and epididymis of young rams into about 200 individuals. Results similar to those of Brown-Séquard and some even more general in nature were obtained.

Recently the beneficial effects obtained from testicular injections have again been reported by Stanley ('21). This observer injected testicular tissue into over 300 men of the San Quentin prison. General beneficial effects similar to those of Brown-Séquard are reported. Controls introduced

to insure that the effects of suggestion were not responsible or at least mixed with the effects from the injection itself are not reported, however, hence it is impossible at the present time to correctly appraise the value of this study. It seems quite probable, however, that the testicular substances are, in large part, at least, responsible for the effects observed and reported.

Animal experiments begun in this laboratory on albino rats indicate that copulatory ability can be restored to impotent males by the injection of testicular tissue. Macerated testis taken from potent males has been injected subcutaneously, by means of a large-bore syringe. In a relatively short time (two to four days) practically every animal so treated became sexually aggressive and a somewhat smaller per cent. of them regained copulatory ability. Similar results have been obtained in several animals in which the testicular grafts failed to become established in their new locations. Failing to establish a blood supply, the grafted tissue became necrotic and sloughed out within 8 or 10 days. Nevertheless, sexual activity including copulation was renewed on the third or fourth day after the transplantation was made. It was always of relatively short duration, lasting in no case observed for more than two or three days.

The exact explanation of the manner in which the effects from testicular juices and tissue injected subcutaneously are produced cannot be given at the present stage of research on this subject. The most favored conjecture is, however, that through the use of the testicular juices or tissues a transference of testicular hormone is effected which has the same libidinous effects on the nervous system and bodily metabolism of its new host that it has in the animal from which it was taken.

Cells Liberating Sexual Hormone

Although the foregoing results point definitely to the testis as the seat of the hormone which underlies sexual behavior it offers no clue as to the identity of the cells responsible for its production. Three distinct kinds of cells are found in the testis: the cytogenic or germinal cells; the sus-

tentacular cells (cells of Sertoli) which serve as nutrient carriers for the germinal cells; and the interstitial cells (cells of Leydig) interspersed between the seminiferous tubules. Various experiments have been devised and many histological studies made for the purpose of determining exactly which of these cells is responsible for the testicular hormone. The majority of studies at the present time point to the interstitial cells as the most probable one of the three. To examine all the data pointing in this direction would be beyond the scope of the present study, yet it will be of interest to note briefly certain lines of experimental studies upon which this belief is founded.

Sexual Behavior of Cryptorchids

One source of evidence as to the cells liberating the sexual hormone is the study of testes from cryptorchid animals. In certain cases of cryptorchids only interstitial cells of the testis are found. Notwithstanding the absence of the other constituents of the testis both the somatic and the behavioristic characters of the male are found to appear and persist. A very noteworthy case of this kind has been reported by Whitehead ('08). He describes the case of a horse from which one scrotal and one abdominal testis had been removed. The horse, now fully mature, did not assume the natural characteristics of the gelding; but contary to expectation he became so spirited and unmanageable that the owner permitted the veterinarian to make another operation to determine whether other testicular tissue remained. A third testis was discovered and removed. Subsequently the horse settled down as any ordinary gelding. Upon sectioning and examining the testis histologically the germinal tissue was found wanting and the sustentacular cells (cells of Sertoli) were in a state of degeneration. The interstitial cells, on the other hand, were well developed and secretory granules were present. It seemed probable to the author, therefore, that the interstitial cells regulated the sexual instincts of the animal in question. Further evidence of a similar nature is furnished by Bouin and Ancel ('03). They have described cases of cryptorchid testes in swine in which only the interstitial cells

were well developed, yet the animals exhibited the typical sexual behavior and structural characteristics of normal animals. Hanes ('18) also reported extensive studies on the testicles of 56 pigs, 7 sheep, and 6 men, showing by histological methods that the interstitial tissue is the most probable seat of the testicular hormone.

X-Ray Treatment of the Testis

The germinal tissue has been eliminated from the possible producers of the hormone through studies made by subjecting the testis to repeated doses of the X-ray. Albers-Schöenberg '(03) working with rabbits and guinea pigs showed that when their testicles were exposed to the action of the X-ray a selective degeneration in the tissues followed. The cells of Leydig and Sertoli remained functional together with the nerves and blood vessels, but total arrest of spermatogenesis resulted. The animals showed normal potency for copulation, but were sterile. Phillips ('04) states that the effects of prolonged action of the X-ray on human testicles is the cause of sterility without alteration of sexual desires. Brown ('05) reports similar findings in the case of 18 attendants who were concerned with the manipulation of X-ray generators. Similar studies of more recent date are in harmony with the foregoing results. So long as the interstitial cells are not injured, no matter what damage is done to other tissues, sexual desire is retained.

Ligation of the Ductus Deferens

With ligation of the ductus deferens complete degeneration of all constituents of the testis other than the interstitial cells has been observed to follow. Bouin and Ancel ('03) report that no change in secondary sexual characteristics or sexual behavior follows the ligation of the ductus deferens in horses and other animals. Shattock and Seligmann ('04) showed that with the occlusion of the ductus deferens in Hertwick rams and fowls the structural and behavioristic sexual characteristics were preserved. Recently a case has been reported by Sand ('21) which is worthy of special consideration because of its direct bearing upon the recently

advocated operation (Steinach) to offset the effects of old age through the ligation of the ductus deferens which causes hypertrophy of the interstitial cells and with hypertrophy comes an increase in output of the testicular hormone. Sand's report is as follows:

Condition of dog prior to operation: Age at time of operation was 12 years and 3 months. From a robust constitution during the first 8 years of his life, he became gradually less resistant to fatigue. This was especially noticeable in the year 1921 when the actual symptoms of senility became pronounced. Movements were retarded, vision began to fail, he became emaciated and the skin became bald. Up to the age of 11 years he was a good hunting dog, but thereafter he became useless. Memory seemed to fail as evidenced by the ease with which he lost his way while hunting. *Sexual appetite, keen in early years, had entirely disappeared.* When taken to the veterinarian for operation the above description was confirmed with respect to the external evidences of senility. Physical examination revealed no signs of diseased organs; he tested negatively for tuberculosis; urine tests showed symptoms of old age.

Operation: On May 23, '21, vasectomy was performed on the left side. On the right, a section of the epididymis was done in a manner which insured the cessation of spermatogenesis.

Subsequent reports: On October 25, the owner furnished a report to the clinic which stated that immediately after the operation the dog was in the same condition from external appearances, as when he was brought to the clinic. It seemed, if anything, that the signs of decrepitude were aggravated. About three to four weeks later, however, an amelioration of the symptoms seemed to appear. The legs grew straighter, the appetite increased, and at the same time the dog took more interest in his environment. During the months of August and September the progress became accentuated. Vision improved. The eyes opened greatly and the scenting became normal. The dog was able to run in good condition. He preceded a bicycle at the rate of 15 kilometers per hour. His interest in other dogs increased. Neck muscles became strengthened—tonic. He offered to play and showed a greater amount of vivacity. *On the 20th of November he copulated.*

Mode and Seat of Action of Hormone

Factual data concerning the mode and seat of action of the testicular hormone are wanting. At the present time, however, it is generally believed that its influence is exercised by direct action upon the central and sympathetic nervous system and through chemical regulation of the general metabolism (Biedl, '13, Vincent, '12, Paton, '18, and others). The evidence upon which these assumptions rest, as we have shown, is indirect and conjectural, being founded primarily upon analogies taken from the actions of other hormones with which investigators are more intimately acquainted.

Clinical and introspective accounts of the influences of the testis when resorted to as a therapeutic measure are somewhat conflicting at the present time. They emphasize in general, however, such points as 'rejuvenating effects,' 'buoyancy of feeling,' 'improvement of general health,' 'improvement in the vegetative functions' and 'the return or strengthening of extinct or waning sexual desires' secured by its use. A correct appraisal of these clinical reports and introspective accounts cannot be accurately made until more objective measures of reputed effects from gonadal therapy have been established.

Experiments on animals tend to indicate that libidinous effects of testicular extracts are not confined to the species from which the substance was originally taken. The glands of any of the laboratory and domestic animals have proved effective when used as extracts. From the standpoint of the type of behavior aroused, however, the testicular hormone is specific as to its ability to evoke masculine behavior irrespective of the sex of the animal into which it is introduced. This has been clearly demonstrated by the studies of artificial hermaphroditism (Steinach, '12, Sand, '18, Moore, '18).

A great deal of conjectural and some experimental data have appeared in the literature pertaining to the relationship which is thought to exist between the testicular hormone and that of other endocrine glands. The available data are still too conflicting to enable one to generalize upon this subject with assurance and these generalizations will be borne out by future experimental studies. For extensive accounts of this subject such standard works on endocrine glands as those of Vincent, Biedl, Paton and Bell may be consulted.

Summary

1. The copulatory response of the male of higher vertebrates may be likened from the standpoint of its neural relations to those complex patterns of congenital behavior typified by the 'scratch reflex' (Sherrington, '06). Although regulated, in part, by neural impulses from the brain and brain-stem, it is improbable, according to recent investigators,

that it is controlled by a special cortical center. The primary elements of this response, erection and ejaculation, are essentially a series of coördinated spinal reflexes involving the lumbo-sacral portions of the cord. Under experimental conditions they can be evoked with the cord transected cephalad to the lumbar segments.

2. The copulatory response differs fundamentally from the 'scratch reflex' and other reflexes of similar nature by virtue of its dependence upon a special gland, the testis, for activation and regulation. Experimental evidence arising from ablation, transplantation, and the injection of testicular tissues or extracts indicate that the testis discharges into the blood stream an internal secretion which controls the sexual responses. It has been assumed that this internal secretion exercises its regulatory influence chiefly through the nervous system, but the mode and seat of action are wholly unknown at the present time.

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THRESHOLDS OF ROTATION[1]

BY RAYMOND DODGE

Wesleyan University, Middletown, Connecticut

The threshold of rotation is an ambiguous concept both with respect to the physical stimulus and to the indicator. The physical facts of rotation may be expressed in terms of angular displacement, angular velocity, and acceleration. In our ignorance of the extent of the general receptor-field for rotation and of the specific neuro-physical mechanisms of the vestibule, any one of these three physical characteristics of rotation, or any combination of them, may be the significant stimulus for the consciousness of rotation and the corresponding reflexes. There is evidence that, on occasion, each one of the three physical characteristics does in fact operate to condition a perception of rotation.

The concept of rotation threshold is further complicated by differences of professional opinion with respect to the relative reliability of the indicators. According as our bias is objective or introspective, the term 'threshold' may refer to compensatory eye-movement or to consciousness of rotation.

The lack of precision of the problem of the threshold of rotation is not an accident but the inevitable consequence of a stage of development. It seemed to us to call for exploration rather than for the massing of data. While by no means complete the exploration of techniques, stimuli, receptor-field, and indicators, has advanced to a point where some practical results are visible and where, if greater precision is desirable, coöperation is needed for detailed special investigations.

[1] The present paper represents part of a research program on some of the elementary conditions of human variability, which was initiated by the support of the Ernest Kempton Adams Research Fellowship of Columbia University. It is printed separately as a part of the research activities of the Committee on Vestibular Research of the National Research Council.

An important and pressing practical bearing of the threshold of rotation relates to the orientation of the flier and to the relative importance, dependability, and possible correction of subjective data for the piloting of airplanes and gliders. There are well-authenticated accounts of aviators making a complete loop in the clouds without knowing it, of emerging from the clouds after making a half loop, flying upside down. Similarly, travelers lost in the desert or in snow fields are commonly reported to circle back to their own tracks. To keep a straight course on land, at sea, or in the air, without some objective point of reference is impossible for any considerable length of time. If this is true, it is of practical use to ask: What is the minimum rotation that the vestibular mechanism may be relied on to detect; under what circumstances does the vestibular mechanism function as an adequate control of locomotion; and how far may it be trained?

Scientific interests are also involved in a study of a rotation threshold. In any complete discussion of a sense mechanism the normal threshold should be included, but in the case of the vestibule there is an unusual scientific motive for the study of threshold. We are still none too sure of the precise mechanics of vestibular stimulation. It is very doubtful if actual movements of a fluid in minute tubes like the semi-circular canals can account for the relatively long continued after-effects of rotation and the long continued post-rotation reflexes. It seems highly improbable that an after-nystagmus which lasts twenty seconds after rotation stops can be conditioned by the momentum of a column of fluid in a canal less than half a millimeter in diameter and about a centimeter and a half long. Actual momentum movements, twenty seconds or more in duration, in such a canal are unthinkable. It is absolutely impossible to account for the newly discovered positive and negative after-images of slow acceleration[1] by any known physical characteristics of the vestibular fluids. As an important datum for a theory of the mechanics of the vestibule we must know the amount and kind of movement that conditions its characteristic

[1] JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 1923, VI., pp. 10–11.

reactions. Further theoretical bearings of our problems include the extent of the receptor-field for rotation, the relative sensitivity of its several parts and the relative reliability of reflex and conscious indicators.

My personal systematic interests emphasize the latter aspect as one phase of the elementary conditions of human variability. Incidentally, the possibility of an unusually direct comparison between the reflex indicator of rotation (vestibular nystagmus) and introspective data seems to offer unusually accurate data in a methodological dilemma.

Extent of the Receptor-field for Rotation

It is commonly held that the receptor-field for rotation focuses in the mechanism of the vestibule. While this mechanism is relatively small, it is complex and highly differentiated. That it is equally sensitive for all three of the physical aspects of rotation, there is at present no evidence. The relative importance of data from the larger receptor-field is quite unsettled. Of that larger field, vision is presumably the most sensitive and reliable factor. In a previous paper[1] it was shown that very slowly accelerated rotation might proceed through from 100° to 200° without being reported by the rotating subject if his eyes were closed. With the eyes open it was possible to report similar rotation to a fraction of one degree. With sufficiently clearly contrasted points of reference the visual data for consciousness of rotation are extraordinarily fine.

It is quite possible that sense data of rotation are also given in audition, in kinesthetic perception, muscle strains, articular sensation, dermal sensations, as well as in consciousness of eye-movements and changing configuration of pressures. Data are occasionally reported relating to movements of the more or less loosely attached parts of the body, especially the contents of the abdomen. All of these data may on occasion be so faint as to be unrecognized and unplaced. Under such circumstances, since vestibular data have no known specific characteristics, it is easy to confuse them with data from the vestibule.

[1] Journal of Experimental Psychology, 1923, VI., pp. 7–15.

Notable illusions of rotation are readily produced by the artificial stimulation of the visual cues to rotation, as was conspicuously shown some years ago in the 'haunted swing' illusion. An analogous illusion is an every-day phenomenon whenever vision reports any slow movement of the environment without jar. One of the most familiar examples is the apparent movement of the observer when a parallel railway train begins to move out of the station. When visual and vestibular data actively conflict one has a more or less disturbing experience which we shall discuss from the photographic records of eye-movements in a subsequent paper. Even when the eyes are closed movements of shadows may possibly give a clue to rotation. But as far as we can discover this clue to rotation is neither delicate nor accurate. As far as our present records go it is negligible.

Auditory data may also function as an index to a rate of rotation which is well below the threshold of the vestibular mechanism. This fact was particularly annoying in our laboratory as we had no sound-proof room. Peculiarly disturbing were the noises of the heating apparatus, snapping of the radiators, and the less intense escape of air and steam. Accidental disturbances, such as the movement of classes, or individuals in the halls, or recitation rooms, were occasionally discovered to function in the complicated sense data of rotation.

Probably the most primitive of all rotation data are the dermal contact sensations. Pressure changes are often referred to by our subjects as clues to the fact of movement, or the sense data of rotation. This was especially true of slight changes in pressure sensation of a knee when it rested lightly and with relaxed thigh muscles against an upright of our rotating platform. Pressure cues were occasionally reported from everyone of the points of contact between the subject and the apparatus. Arm-rest, head-rest, and seat were especially prominent in the reports. Joint sensations were also occasionally reported. In a word, the sudden onset of rotation regularly produced inertia data from a considerable variety of organs, as well as from the vestibule.

Some of these data from the wide receptor-field have a much more favorable leverage than occurs in the vestibule. Slight knee pressure with relaxed thigh mucles is an illustration. In the case in point the thigh joint was practically over the center of rotation as were the semi-circular canals. The knee consequently was eccentric the entire length of the thigh and in a relatively favorable position for the operation of inertia. It proved to be on the whole a considerably more delicate receptor for rotation than the vestibular mechanism. We naturally tried to eliminate such possibilities in subsequent experiments. In our ordinary consciousness of rotation all of these non-vestibular data bulk large in comparison with the ill-defined data from the vestibule. The relative sensitivity of these various parts of the receptor-field deserves more systematic investigation than we were able to give.

The question whether any of these data affects the rotation reflexes deserves special attention. We have pointed out in a previous paper a general similarity between the nystagmus of rotation and the nystagmus of pursuit. They are often not differentiable in photographic records. Only their latencies and their course are different. Under these circumstances it seemed impracticable to answer the question whether visual data of rotation produced a reflex nystagmus. The auditory data, however, were studied by a preliminary exploration.

Auditory Receptor-field for Rotation

The apparatus for studying the question whether there was a reflex response to the effect of rotation on the auditory part of the receptor-field consisted of two parts, a revolving sound-cage to give the auditory stimuli and an eye recording apparatus. The latter did not differ in essentials from the eye recording apparatus already described in previous papers.[1] In this case, however, since the subject was to be stationary, the recording camera was firmly mounted on a heavy table instead of on the revolving platform. A head-rest, similar

[1] 'Latent Time of Compensatory Eye-movements,' Journal of Experimental Psychology, 1921, *IV.*, pp. 247 fol.

to that provided on the revolving platform, was placed in front of the camera at a suitable distance. The recording instrument was our mirror-recorder for photographing the movements of closed eyes.[1]

The stimulating part of the apparatus was a sound cage which was revolved by hand. The sound-cage carried a vibrating telephone receiver or a small electric buzzer of the watch-case type at an average distance of fifty centimeters from the subject. It proved difficult to produce an illusion of subjective rotation from the movements of this sound producing instrument as it revolved around the subject. This was probably due in part to the fact that the sound shadow of the recording camera passed the observer once each revolution when the sound producing instrument was directly in front. This sound shadow certainly disturbed the normal progress of the sound and led to an illusion that the sound instead of traveling in a circle went out to some distance and returned, changing its apparent path in a more or less complex way. The progression of the sound was clearest when it was behind the subject since in that position there was no sound shadow. There was, however, some difficulty in the subject's locating the sound behind him. It often seemed to oscillate back and forth in front. In addition to these factors which tended to prevent clear cut perception of an evenly rotating sound, an additional factor preventing the transfer of rotation from sound to subject was given in the latter's sophistication. The subject knew that he was seated at a heavy oak table which rested on the floor, that his head was supported by a head-rest on that table and that it was impossible for him to rotate. This produced a subjective set which was more or less inimical to the illusion of subjective rotation.

In spite of these technical faults of the apparatus, there was occasionally an illusion of subjective motion; that is to say, instead of the sound traveling around the subject the subject seemed momentarily to float independent of contact with the table, head-rest, and seat, and himself to rotate

[1]Journal of Experimental Psychology, 1921, *IV.*, pp. 165 fol.

while the sound stood still. Unfortunately, there was no regular premonition of these moments and they were at best fleeting. It was consequently an accident when they coincided with a moment of photographic registration of the eye-movements. Possibly the ideal arrangement would have been to take continuous records of eye-movements and to have noted the illusions of rotation on these records. Such a procedure, however, would have been expensive in time and photographic material, and it would have involved a continuous recording camera which we did not at that time possess. The records that we did take were intermittent records on sensitized paper, 5 in. x 7 in. in size. In spite of this inadequacy of the recording camera we have several cases in which subjective illusion and the eye record do in fact coincide. Two of the occasional coincidences of this sort are reproduced in Plate I., Records 1 and 2. These records show real nystagmoid eye-movements. There is no doubt about that. Whether they were exactly coincident with the illusion of subjective rotation or not we were unable to determine, but the coincidence was at least approximate.

In the effort to overcome the persistent mental set which was occasioned by knowledge of the impossibility of rotation, the instrument was redesigned and adapted to the rotating platform in the following manner. The sound-cage instead of being elevated above the rotating platform, where it would have interfered with the wire stays and electrical connections, was built up from the base of the rotating platform. To this end a board was cut to fit over the cylindrical stem of the supporting tripod below the rotating platform. An electrical buzzer was attached to the board and was counter-balanced by weights to keep the board in equilibrium. Under these circumstances it was possible to rotate at will either sound-cage or subject, or both subject and sound-cage. This new position of the sound-cage had a further advantage that the sound shadows from the recording camera were very much reduced. With this arrangement somewhat more numerous illusions of rotation were actually produced than with the previous one. But it seemed impossible to prevent some

secondary clues, partly due to slight vibrations of the platform when the subject was started in rotation and partly due to the noises when the sound-cage was moved. In spite of all of these unfavorable circumstances the fact that occasionally nystagmoid movements were produced is the point to be emphasized.

Record 3 of Plate I. represents a short series of experiments with far-reaching implications of facilitation and rivalry if further experiments corroborate these results. The series grew out of the effort to prevent the sophistication of the subject as to the fact of his own rotation or stillness while the sound-cage was rotated around him. For this purpose relatively small oscillations of the subject were superadded during the continuous rotation of the sound-cage in one direction. The experiment aimed to create a crucial situation when one might find either one of the following significant alternatives. If the oscillation of the subject is the only factor influencing the ocular movements one would expect a vestibular nystagmus changing the direction of its deviation or compensatory phase with the changes in the direction of oscillation. If, however, the sound movements also influence the eye-movements one would expect to find a corresponding modification of the vestibular nystagmus. An extreme case of such influence would involve the suppression of the vestibular deviation which compensated for one direction of rotation and the substitution of a deviation corresponding to the rotation of the sound. Lesser degrees of such influence would involve the diminution of the vestibular deviation in one direction and its exaggeration in the direction corresponding with the rotation of sound. As a matter of fact both degrees of modification of vestibular nystagmus are found in Plate I., Record 3, which was taken from an untrained subject (subject *H*). The moments of extreme influence are lettered *A*. Moments of lesser influence are lettered *B*. Moments of deviation which were conditioned purely by sound are lettered *C*. The series, of which Record 3 is a part, was a purely exploratory one. Before these results can be regarded as definitive an extensive

critical study of this phenomenon would be necessary. The preliminary results indicate that such a study is worth while. It seems possible that the ocular mechanisms offer particularly favorable conditions for a study of facilitation and rivalry in a complex nervous system.

The conditions of this nystagmus from moving sounds obviously could not have been vestibular in origin. It must have arisen from the illusory consciousness of rotation which is presumptively a cerebral function. Even under the best technical conditions it is very doubtful it it can be demonstrated whether such nystagmus is a true reflex or not. It may be of the nature of an ocular pursuit in response to the illusion of rotation. The difficulty of determining between ocular pursuit and reflex nystagmus has already been mentioned. As we previously stated, their photographs are often identical and they can be distinguished best by their latency. In our experiments, measurements of the incidence of the illusion could not be recorded with sufficient precision to differentiate a reflex from a reaction. It remains entirely possible that the occasion of the nystagmus was an imaginary movement of the environment due to the illusion of subjective rotation. It is also possible that the nystagmus was due to the visual imagery of the moving electric buzzer or some other part of the sound-cage. The whole experience is so fleeting and so difficult to obtain experimentally that a more exact description was not attempted. There is, however, no doubt that under favorable circumstances the illusion of rotation and a corresponding deviation of the eyes may be conditioned by auditory stimuli.

The artificial production of dermal and kinesthetic data of rotation proved impossible with any means at our disposal. Consequently, we have no new information as to whether or not they alone could produce either nystagmoid eye-movements or illusions of rotation.

Our ordinary data of rotation are doubtless complex. Vision, sound, contact, kinesthetic, and vestibular data, commonly coöperate. Artificial data from any single experimentally selected factor of this receptor-complex would

be opposed regularly by antagonistic data from all the rest. Consequently, the stimulation of a single factor would only occasionally condition an illusion of rotation, when for some reason the negative factors from the rest of the field were inhibited or the selected factor was strongly reinforced. In spite of these experimental difficulties the relative importance of vestibular data and data from the other parts of the receptor-field seems fairly clear. Only occasionally did the sound displacement data occasion ocular deviation, or the illusion of rotation, when they were opposed by the data of standing still from the rest of the receptor-field. Electrical or thermal stimulation of the vestibule on the contrary regularly produces illusions of rotation and ocular reflexes even when it is opposed by negative data from all the rest of the receptor-field. Apparently, something analogous occurs in a common tendency of amateur navigators in the fog, which leads them to distrust the accuracy of the compass, when vestibular data indicate that they have been going straight. Similarly, air-pilots may fail to realize from the tension of straps and other kinesthetic data that they are flying upside down when their rotation has been too slow to be reported by the vestibule.

There seems to be no intrinsic reason, however, why any part of the receptor-field may not be reinforced or inhibited by proper training. The expert navigator trusts his compass implicitly in spite of negative indications from the vestibule. We have already seen that vestibular reflexes and consciousness of rotation may be inhibited by training.[1] It is highly probable that kinesthetic and pressure data could be made to control conduct in the air, if systematic training were designed for that result.

How far data from various parts of the receptor-field may reinforce each other we have only incidental experiences to indicate. Consciousness of rotation at or near the threshold was undoubtedly aided by environmental sounds and pressures of various sorts. A systematic quantitative study of these reinforcements and inhibitions would be illuminating but difficult.

[1]JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 1923, VI., pp. 15 fol.

Thresholds of the Vestibular Mechanism

Three separate experimental stimulus-forms were utilized in our study of vestibular thresholds. The first was a succession of five and ten degree movements with sudden onset and *constant angular velocity*. The second was a series of ten degrees rotary movements approximating in angular acceleration and deceleration a *true sine wave*. The third was a succession of movements of considerably greater angular extent in which the *arithmetical acceleration was approximately constant* for twenty degrees of rotation. All three of these stimulus forms depended on the drive of a constant speed motor which operated on an offset arm from the rotating platform at a distance of one meter from the axis of rotation.

Constant Speed Motor

The effort to find a suitable constant speed motor delayed the experiments many weeks. It was highly important not only that the motor should be reliable within the limits of our experimental requirements but that it should be noiseless and especially that no noise should be produced by changing its load. Pursuant to statements of Dr. Seashore on the accuracy of high grade phonograph motors and because they operate quietly we were led to try out several types. There is a real need for a critical comparison of different makes of phonograph motors for psychological laboratory use. We were limited to relatively few but in that limited exploration of the relative value of different makes we found one that seemed eminently satisfactory at a reasonable cost. All the electric phonograph motors that we tried made too much noise. The hum of the magnet was usually audible even when there was no noticeable noise of moving parts. The best electric motor in our experience was the one built by the Pathé Company on the plan of an electric meter. It consists of a disk rotating in the magnetic field produced by an alternating current. The hum of this motor is very faint and there is no noticeable noise of moving parts. Unfortunately, the magnet noises which result from the addition of a load

in moving the chair were reported by several observers. The heavy Pathé spring motor, on the contrary, operated at moderate speed entirely without noises which could be detected at a distance of a meter. The subject was not able to state when the motor started or when it stopped. There was no noticeable change when a load was added to it. The strength of the heavy spring was at all times more than was necessary to operate the controlling device, irrespective of the work that the motor was required to do in producing slow movements of the platform.

The driving pulleys were attached directly to the main shaft of the phonograph motor. They consisted of a cone of four pulleys, respectively, one fourth, one half, three fourths, and one inch in diameter at the foot of the V-shaped grooves. This gave the possibility of four variations in speed according as the belt was driven by one or another of these pulleys without alteration of the device which controlled the speed of the motor. We adjusted the speed of the motor so that the smallest pulley, applied directly to the offset arm of the rotating platform one meter from its axis of rotation, gave an angular velocity of one degree a second. The several pulleys gave corresponding angular velocities up to four degrees a second without readjusting the motor control.

Stimulus Forms

The three physical factors involved in rotation, namely, angular velocity, angular displacement, and angular acceleration are not entirely separable although each may be varied independently of the others. With any given angular velocity the total angular displacement is a function of time. But unfortunately, the duration of the stimulus is not the only stimulus phenomenon that is conditioned by protracted slow rotation. Increased angular displacement increases the probable interaction of various reinforcing factors such as change in the apparent position of sounds, direction of air currents, heat radiators from adjacent walls, and the like. It also produces definite adaptation phenomena. Every stimulus must reach

its maximum velocity by some sort of acceleration. Small angular velocity may involve high acceleration for short periods. For example, an angular velocity of one degree per second may be attained in a tenth of a second. This would represent a stimulation onset of relatively high angular acceleration for a short period of time. Conversely, protracted slow angular acceleration might reach an angular velocity of indefinite magnitude if it were continued long enough. The effort to experimentally explore the relative effects of angular velocity and angular acceleration in vestibular stimulation gave rise to three stimulus forms.

Stimulus Form I (Sudden Onset and Constant Velocity)

In the first stimulus form (sudden onset and constant velocity) a continuous belt between the pulleys on the axis of the constant speed motor and a friction pulley in the hand of the experimenter was connected with the offset arm. According as the connection between the belt and the arm was made with the outgoing or returning side of the continuous belt the platform moved clockwise or counter-clockwise. We realized that the connection of the belt with the offset arm must be noiseless, positive, and immediate in its operation. We, consequently, experimented with a number of clamp devices and finally came to use a small peg on the offset arm, covered with surgeon's plaster, sticky side out. The thread belt moving toward or away from the motor could be brought into contact with this surface effectively and noiselessly with a minimum of effort. When the connection was made there was no slip and no noise. No serious additional friction was imposed by this device on the motor, except the friction of the platform bearings.

Photographic records of the onset showed that, though the velocity did in fact remain satisfactorily uniform, there was considerable variation from time to time in the onset acceleration. Practice in manipulation diminished this variation but it was inherent in the method.

Stimulus-form II (Sine Wave Acceleration)

In order to standardize the acceleration a secondary driving-wheel was interposed between the motor and the offset arm of the rotating platform. This secondary driving-wheel was connected with the offset arm by a rigid driving-rod. The driving-rod operated through cone bearings, one on the offset arm and one on the periphery of the wheel. The diameter of the wheel at the base of the V-shaped groove was the length of a double sine of five degrees of rotation of the rotating platform measured on the arc described by the cone-bearing on the offset arm. That is to say, one-half revolution of the driving-wheel would move the rotating platform through an arc of ten degrees. Continuous rotation of the driving-wheel under these circumstances oscillated the platform back and forth through an arc of ten degrees with a maximum velocity of one, two, three and four degrees per second according as the belt was on one or another of the cone of pulleys at the motor. In routine experiments the oscillations were interrupted at the extremes of each swing at a time when the angular velocity of the rotating platform was zero. The consequent form of the rotary movement may be described as follows: starting at zero the rotation reached a maximum velocity corresponding to the speed of the pulleys on the motor and declined again to zero as the cone bearing on the wheel reached its diametrically extreme position. In order to prevent the subject from rationalizing the sequence of clockwise and counter-clockwise rotations and prejudging what direction the next movement would take, the driving rod was fitted with two cone bearings which were separated by the diameter of the driving-wheel. By this device, after a clockwise movement of ten degrees, a shift of the driving-rod to the second bearing would permit a second clockwise movement of ten degrees, if contact between the driving bar and the pulley were interrupted entirely until the driving wheel reached its original position. With this arrangement the sequence of movements could not be predicted by the subject. The order of directions was determined by chance.

Stimulus-form III (Arithmetical Acceleration)

Our first effort to produce arithmetical acceleration was to interpose between the motor and the offset arm of the rotating platform a screw-shaped pulley which was turned on the surface of a cone. If this conical screw accelerator was driven at a regular rate by the motor, a thread from the offset arm of the rotating platform winding up on the screw would produce a regular acceleration corresponding to the continually changing diameters of the cone. This arrangement gave a perfectly even acceleration of the platform after it once started. Unfortunately, the beginning of motion regularly produced a slight but often perceptible jar. This resulted from the construction of the screw accelerator. The winding process did not start at absolute zero but at a velocity corresponding to the diameter of the little shaft on which the screw was turned. We had hoped that this initial inequality would be so slight as to be insignificant. When this proved not to be the case, the jar was completely eliminated by combining the screw accelerator and the driving-wheel of stimulus-form II. This cost the acceleration something of its previous mathematical exactitude, but the onset was always imperceptible.

No combination of driving-wheel and conical pulley that we worked out would give an absolutely even acceleration. Theoretical plotting of the curves and empirical corrections from photographic records showed that it was desirable to flatten the pulley so that the radius of curvature should gradually increase for the first few degrees of rotation of the chair. The accompanying photograph shows the best configuration that we were able to obtain. It looks to be perfectly even. An analysis of the rotation indicator of two photographic records shows the series of accelerations by two second intervals as given in Table I.

Table I shows the acceleration of rotation by combined conical screw accelerator and flattened driving-wheel, by two second intervals, reduced to hundredths of a degree. This was the unit of measurement.

TABLE I

11	11
9	10
8	10
10	12
11	10
12	13
13	10
14	12
10	10
11	13
11	10
9	9
10	10
Av. 10.7	10.7
M.V. 1.3	M.V. 1.1

Photographic records of these several forms of stimulus are shown in Plate II, Records 1 and 2.

METHOD OF REPORT IN ROTATION THRESHOLD EXPERIMENTS

The manner of reporting awareness of rotation in rotation experiments is a matter of some importance. The simplest method of report might seem to be vocal, such as 'right,' or 'left,' 'clockwise,' or 'counter-clockwise.' Such vocal reports, however, demand a certain division of attention. They are of the nature of distractions from the main experiment. That is to say, the subject must not only perceive the direction of rotation but he must be careful to select the correct designation. Surprising as it may seem, the designations, right and left, required in many subjects considerable conscious effort. Nevertheless, once practiced, in series of discontinuous rotations, verbal reports are probably satisfactory.

The use of periodic verbal reports during protracted rotation on the contrary have certain theoretical and practical objections. Our attention was called to these difficulties by the statement of one of our observers that speech disturbed his observation of a protracted slow rotation. This was for a while inexplicable except on the theory of distraction of attention. In view of other experiences we are inclined to believe that a real interference from peripheral sources may accompany speech. Observation showed that all respiration moved the head more or less and produced undulatory

illusions in protracted rotation. The best observations demanded relatively low respiration. Under these circumstances it is probable that articulation through its effect on respiration and consequent movements of the head introduces real vestibular disturbances that would tend to confuse threshold phenomena.

Wherever it was necessary to obtain actual records of the reports as part of the photographic record of the experiment we used manual report, *i.e.*, the pressing of keys. Like verbal report, manual report is capable of producing movement of trunk and head and should be restricted to finger movements of such a character that there was no consequent displacement of the body. The finger movement which proved most satisfactory was that of pressing a key between the thumb and fingers. Slight vertical movements of the fingers with the arms supported by proper rests also proved satisfactory.

Three forms of manual report were used for different purposes in those threshold experiments in which photographic records were taken. The first form was a predetermined arbitrary signal produced by pressing a telegraphic key between the thumb and fingers, either once for right movement (clockwise) or twice for left movement (counterclockwise). This telegraphic key was in series with the recording lamp and the breaks in the circuit appeared on the record as an interruption of the line which indicated rotation. This arbitrary signal did not prove to be satisfactory. It was unnatural, required practice, too much attention, and led to occasional false reactions. The second and third methods involved movements of the right and left hand respectively for right and left rotation. This method of reporting proved entirely natural, required no practice, and occasioned no unintended reactions. The second manual method involved pressing keys which lay under the right or left hand respectively, and which were connected by threads with the mountings of minute, concave mirrors. These mirrors reflected a recording beam on the right and left hand side of the record sheet. Judgments of rotation either to

the right or left were indicated by displacement of the appropriate record line. Such records are reproduced in Plate III., Records 1 and 2. Judgments of no movement were indicated by both record lines remaining in their primary positions. The third manual method provided a telegraphic key for each hand. Pressing the right hand key interrupted permanently the electric circuit to the recording lamp and stopped the record of rotation. Pressing the left hand broke and immediately remade the lamp circuit, giving a short interruption of the record of rotation. These differentiated interruptions were entirely automatic and gave entirely satisfactory records. One added advantage of the manual report was the possibility of recording reaction latency as well as the judgment of movement and its direction. Not much weight is given to these measurements of latency, but they furnish some subsidiary evidence with respect to the threshold of rotation.

Vestibular nystagmus is doubtless the most natural indicator of rotation. It requires no attention nor voluntary effort. As a reflex it would seem to be the best possible indicator. Our experience in the study of the effects of repeated rotation led us to doubt the reliability of vestibular nystagmus in serial experiments. Nevertheless, a considerable number of ocular reactions were taken in conjunction with manual reactions. A comparison of the two methods of report has certain theoretical value in connection with the discussion between the thoroughgoing objectivists and introspectionists. Wherever taken the ocular reflexes were registered by the mirror-recorder. Two records are reproduced in Plate III., Records 1 and 2.

These records are the first and seventh, respectively, in a series of ten. Whereas in the first record the nystagmus of rotation and of stopping is clearly marked, in the seventh, taken at the same angular velocity, the nystagmus has almost disappeared. Similar changes occurred in all serial records.

It is somewhat surprising and, in view of certain pretensions of the extreme objective school, it is quite illuminating that, while the reflex tended to disappear, introspective

indications of rotation were as accurate in the later records as they were in the first when the reflex was present.

Thresholds of Even Rotation with Sudden Onset

Rotation with sudden onset was produced by the mechanism of the first stimulus form, already described. That is, a continuous belt from the pulley of the motor was momentarily brought into contact with the offset arm and rotated the platform and the subject clockwise, or counter-clockwise, five or ten degrees according to a prearranged series of successive stimuli. The subject was instructed to report every change in his apparent condition of rest or motion. The velocities used were one, two, three, and four degrees of rotation a second. Reports were held to be correct when the report of rest or motion in either direction fell within any part of the period covered by the objective facts. That is to say, if during any period of rest or motion it was correctly and unambiguously reported the report was held to be correct however late it may have come in the period on which report was made. In all subjects 1° per second yielded an average of less than fifty per cent. of correct reports. For three subjects out of four, 2° averaged over fifty per cent. of correct reports. The details of these reports are shown in Table II. These records indicate that the threshold of rotation with sudden onset lies somewhere between one and two degrees per second. If one assumes that with three possible answers, clockwise, counter-clockwise, and still, the point of pure chance would lie at thirty-three per cent. correct answers, then the theoretical threshold would lie close to one degree per second. It should be noted, however, that for practical purposes the incidence of correct interpretation of vestibular data of fifty per cent. would be useless. It would mean that a subject was wrong just as often as he was right and the vestibular data would be absolutely unreliable. For practical purposes, consequently, the threshold of serviceable stimulation would lie close to 2° per second. Even at double this rate, however, it should be remembered that the vestibular data are not entirely reliable.

TABLE II

PERCENTAGE OF CORRECT VERBAL REPORTS OF CHANGES IN ROTATION, SUDDEN ONSET AND STOP

1° per second

B	JSF	N	RD	W
42		33	22	
33		31	55	
31	No	28	55	No
25	records	28	22	records
55		39	—	
Average 37		32	39	

2° per second

		56	58	
		72	67	
No	69	81	70	25
records	58	64	45	42
	31	72	64	47
Average.....	53	69	61	38

The procedure in these experiments was as follows: with the subject in position, eyes closed, head against the head-rest, arms on the arm-rests, after a ready signal, the platform was rotated by the belt from the motor at a speed of one, two, three and four degrees per second, either five or ten degrees clockwise or counter-clockwise according to a prearranged program. A five second period of no rotation intervened before each period of rotation. The prearranged schedule of rotations and pauses was plotted on cross section paper so that the experimenter had before him not only the program and plan of rotation but a record-sheet on which the responses of the subject could be noted as they were made, at approximately the correct moment of the process which was reported.

A number of interesting phenomena were disclosed by a study of these records. One of the most notable and one of the most frequent errors was the failure to note the actual rotation but to report as true motion the illusion of reversal after rotation had ceased. That is to say, slow clockwise rotation of ten degrees might pass unnoticed, but when it

stopped the subject would be apt to report counter-clockwise rotation from the illusion of stopping. Similar errors might be disastrous in flying. A related phenomenon was more persistent, lasting on occasion through three of four changes of rotation. If, for example, the subject reported 'still' when he was moving clockwise, and 'counter-clockwise' when he stopped, he would not infrequently report 'still' when the movement was again clockwise. Occasionally a false orientation of this sort would reach further and false reports would be continued for several successive changes in the rotation. The rotation changes would be clearly distinguishable to the subject as changes. Interpretation of the sensory data proved less easy, or rather, less reliable. With more rapid rotations the subject frequently noticed a difference between onset and continued rotation. One subject reported 'it starts vigorously and disappears or fades away as though in the air.' Similar reports were not infrequent. This emphasized the necessity of experimenting with the second stimulus form.

Another series of threshold experiments with sudden onset and even rotation included the photographic records of eye-movements, manual reports of the second type, and rotation indicators. Each complete record lasted approximately fifty seconds. While the number of rotation changes within this period was necessarily few, the graphic method of report provided for much closer estimates of the perception of rotation and rest.

Consequently, in these experiments we did not merely count the number of right and false reports; but estimated the degree of correctness of the reports by counting the number of times that the two second time-lines occurred during correct reports of rest or motion as indicated by the manual method. Parts of two records are reproduced in Plate III. The percentages of correct judgments by two second intervals are given in Table III.

The fatigue experiments show the effect of beginning the series of judgments one minute after the series of rotations commenced.

Table III

Per cent Correct Judgments by 2 in. Intervals, Rapid Onset, Unknown Series of Speeds and Directions.

N				RD			
1° per second	2°	3°	4°	1°	2°	3°	4°
35	81	65	81	31	41		
27	50	54	96	10	20		
50				26	50		
46				37	50		
46	90	76	86	18	32		
62		71		54	32		
43				27	59		
				41	50		
54	72	67	92	59	18		
33	58	50	92	50			
16				63	77	83	62
12				65	73	70	50
				40			
				23			
				30	73	86	93
				75	63	27	90
Average, 39	70	64	89	41	49	66	74
Fatigue Experiments							
28							
22	75	44	93				
41	56	67	65				
Average, 30	65	55	79				

Thresholds of Rotation with Sine Wave Accelerations

The third experiment resembled the second except that the onset and stop were gradual instead of sudden. Rotation was produced by the driving-wheel. It was always ten degrees in extent and had the approximate form of a sine wave acceleration (see Plate II., Record 1). The results of this experiment are given in Table IV.

Perception of Oscillation

Following the precedent of our previous study of the effect of protracted rotation it seemed worth the effort to discover how the perception of oscillation differed from the threshold of rotation. The mechanical conditions for such an experiment were already furnished by the driving-wheel

with the driving-rod connection between wheel and offset arm. If the driving-wheel was permitted to rotate continuously the platform and subject were oscillated back and forth through an angular distance that was determined by the diameter of the driving-wheel and the length of the offset arm, with a frequency that was determined by the speed of

TABLE IV

PERCENTAGE OF CORRECT VERBAL REPORTS OF CHANGES IN ROTATION. GRADUAL ONSET AND STOP

Maximum Speed	N	RD	JSF	W
1° per second	37	49	—	—
2° per second	65	44	—	—
	72	65	54	54
	80	48	49	24
	58	59	—	—
	72	54	—	—
	73	44	—	—
Average	70	52	51	39
3° per second	88	51	—	62.5
4° per second	71	95	—	69.8

the driving-wheel. Physically, such rotations took the form of harmonic oscillations in approximate sine waves of acceleration and deceleration. This wave form was only approximate since a true sine wave form would have required a driving-rod of infinite length between the driving-wheel and offset arm. Moving the axis of attachment on the driving-wheel toward its center by distances of one-half and three-quarters of its radius, respectively, reduced the amplitude and maximum velocity of oscillation in direct ratio without varying the frequency. In this manner three oscillation forms were obtained for each of the four normal speeds of the drive pulley as they were produced by the four pulleys on the axis of the constant speed motor.

Oscillation as contrasted with simple rotation exaggerated the importance of the acceleration in distinction from the

angular velocity component of the stimulus. In our ignorance of the exact physics of vestibular stimulation the physical theory cannot be followed to its logical conclusion. But the results of the experiment leave no doubt of the importance of the acceleration feature. The effects of oscillating the walls of the vestibule against the momentum of the vestibular fluids would increase the total relative pressures by an amount which would depend on the frictional acceleration of the fluids. In other words, in a frictionless system in which the walls of the container move around a stationary fluid, maximum relative motion would coincide with maximum motion of the walls. Given a frictional acceleration of the fluids, however, which was almost equal to the angular displacement of the walls, then the greatest relative motion would occur when the walls suddenly reversed their direction. Under the latter circumstances one would also obtain markedly increased pressures against the appropriate walls of the vestibule.

The results of these oscillation experiments, as exhibited in Table V., seem to show a bewildering lack of regularity. Some facts, however, are conspicuously clear. In the first

TABLE V

Table V shows the percentage of correct judgments of direction of movement during oscillations of various amplitudes and frequencies. It also shows average reaction latencies in seconds, measured from the beginning of each oscillation.

Maximum Velocity	1° per Second			2° per Second			3° per Second			4° per Second		
Measured rate of oscillation	32″			16″			11.4″			8.4″		
One quarter oscillation	8″			4″			2.8″			2.1″		
Amplitude in degrees	2.5	5	10	2.5	5	10	2.5	5	10	2.5	5	10
Maximum[1] velocity, deg. per 1 sec.	.25	.5	1	.5	1	2	.75	1.5	3	1	2	4
Subject N:												
Per cent. right	40	50	86	8	33	96	44	96	100	72	82	54
Latent time in seconds	10	4.3	1.9	(.5)	2.8	1.2	3.1	1.6	1.9	1.5	1.7	1.6
Subject RD:												
Per cent. right	40	50	43	3	7	31	14	0	71	0	70	66
Latent time in seconds	3	7	10	5.7	5	2.4	.5	—	2	—	1.6	2

[1] Speed of driving-wheel in terms of angular velocity of the platform.

place, the individual differences between N, the graduate student, and RD, the older subject (myself), are more conspicuous in these oscillations than in any other phase of the threshold experiments. In both cases, however, the threshold for oscillation stimulus seems to be much lower than for direct rotation. In the case of subject N it lies conspicuously below a maximum velocity of one degree per second. In the case of RD the data are conflicting for reasons which will be discussed presently. But the fact that fifty per cent. of correct answers were given at a maximum velocity of one-half degree per second cannot be overlooked. A third obvious fact is the extremely long reaction latencies, especially in the case of RD. Analysis of the relation between these reaction latencies and the frequency of right judgments shows that the reaction latency may have a profound effect on the percentage of correct judgments.

The most conspicuous fault in the record of RD is found in cases of small amplitudes of the more rapid oscillations. In these cases there was zero ability to distinguish either oscillatory rhythm or the direction of movement. This seemed inexplicable until we took into account the long reaction latencies of RD. The average reaction time to oscillation in his case was 3.9 seconds. The most rapid double oscillation lasted 8.4″. At this rate each phase of acceleration would last 2.1″, which was considerably shorter than the reaction latency of RD. Under such circumstances it is a defensible supposition that increased demands on discrimination with a presumptive lengthening of reaction time would bring each successive reaction within the influence of a phase of oscillation which was different from that by which it was initiated. Confusion would seem to be inevitable. It is in fact shown by the notable breakdown of correct judgments with oscillations of small amplitudes in both the higher two speeds.

The more rapid reactions of subject N free his record from extreme disturbances of this sort. Under only one of the experimental circumstances did his average reaction time substantially exceed the duration of a single phase of oscilla-

tion. But even in his case it is conspicuous that the highest percentage of correct judgments is not found in the case of most rapid oscillation but rather in the 10° movements at lower speeds.

Perception of Arithmetical Acceleration

There remains to be considered the perceptibility of arithmetically accelerated rotation. As it was produced by our combination of driving-wheel and conical screw accelerator this arrangement developed maximum angular velocity only after approximately 20° of rotation at a uniform rate of acceleration. The percentages of correct reports of rotation series, in which five clockwise, five counter-clockwise rotations, and five similar periods of no rotation followed each other in chance order, are shown in Table VI.

Table VI

Percentages of Right Responses During Slow Accelerations

Maximum Velocity per Second	Subject N			Subject RD			Subject F			
	2°	3°	4°	2°	3°	4°	1°	2°	3°	4°
	53	67	93	33	20	87	60	93	93	80
	47	73	93	13	40	40	80	73	73	93
	66	67	87	40	53	73	70	83	83	86
	60	80	87	47	53	53	93	80		
							60			
Average	56	72	90	33	41	63	73	82	83	86

Table VI. shows large individual differences of sensitivity to the conditions which were presented in this experiment. Precautions to prevent extraneous data for the perception of rotation were taken as follows. Cotton was put into the ears of all subjects to shut out slight noises of the movements of the operator, etc. A motor fan, which stood on the rotating platform, was run during the experiment to cover any mechanical indications of motion that might have come from slight vibrations of the platform. Head and arm-rests were used as in previous experiments. Only one warning signal for each series was given. That signal preceded a series.

The most conspicuous phenomenon of this group of experiments was the peculiar and, in our experience, unique sensitivity of subject F. Our effort to discover the basis of this amazing sensitivity included a variety of modifications of the conditions of the experiment. These may be enumerated as follows: The subject's head was completely covered to shut out supposititious temperature radiations. Cushions were used on the seat, head and arm-rests to decrease contact changes. Head and knee contacts were eliminated. A telephonic head-set was worn giving a loud buzzing of the alternating current. Special blinders excluded all possible clews from shadows or other visual data. The last item in the 2° per second column and the last two items in the 1° per second column show the percentage of right answers after all these special precautions were taken. The conditions of the unusual sensitivity of subject F to gradually accelerated rotation were not discovered. He was an unusually conscientious and intelligent undergraduate and expressed himself concerning the phenomenon as follows: "I do not seem to feel any motion but I realize that I have changed my position in space." He conjectured that his experience in fancy diving had perhaps given him some unusual training in space orientation which he was unable to explain. The subject stated that he was able to keep his direction on the water in fog with a facility which surprised both himself and his companions. Tests of a colleague on the swimming team, also a skillful diver, showed no parallel sensitivity. Exceptional cases such as that of subject F ought to prove of peculiar value wherever the ability to keep orientation is of significance. Both the subject's introspection and his previous records as given in Table IV. would seem to indicate that we were not dealing in his case with mere vestibular functions.

General Conclusions

A summary of the percentages of correct judgment of rotation under the varying circumstances of our experiments is given in Table VII.

TABLE VII

SUMMARY OF PERCENTAGES OF CORRECT JUDGMENTS OF ROTATION UNDER VARIOUS CIRCUMSTANCES OF OUR EXPERIMENTS

Subject N				Subject RD			
Rapid Onset							
1°	2°	3°	4°	1°	2°	3°	4°
32 39	69 70	64	89	39 41	61 49	66	74
Sine Wave Onset							
37	70	88	71	49	52	51	95
Oscillation 10°							
86	96	100	54	43	31	71	66
Arithmetical Acceleration							
—	56	72	90	—	33	41	63

Under our experimental conditions, the threshold for rotation of rapid onset seems to be somewhere between one and two degrees per second, but a velocity of four degrees per second was too slow to produce uniformly correct judgments of rotation. Real assurance of the correctness of judgment of rotation obviously depends on angular velocity exceeding four degrees per second.

The difference between rotations of sudden onset and rotations of similar maximum velocity whose acceleration had the form of sine waves appears to be negligible within the limits of our experiments. Arithmetical acceleration, on the contrary, presented unfavorable conditions for the perception of rotation in the case of subject RD and favorable conditions for subject F.

The most irregular results occured in connection with the oscillatory rotations.

Our exploration of the thresholds of rotation represents only rough, though probably useful, approximations. The investigation of an absolute vestibular threshold for which it

has prepared the way would require the elimination of the numerous sources of error which became clear in our experiments. Definitive measurements demand a sound and light proof room with felt walls to prevent temperature radiations. The driving mechanism should be outside the sound-proof room. The rotation should have definite configuration of onset and stop, probably of the sine wave form. The axis of rotation must be strictly vertical and the rotation must be free from jar and vibration. We know of no practicable means for eliminating those data of rotation that come from the dermal and kinesthetic extensions of the receptor-field. Report indicators should be natural and without disturbing influence on vestibular function. Our experience favors manual indicators. For theoretical purposes warning signals should doubtless precede each rotation.

If a simple test of the individual differences should become desirable it would probably be sufficient to limit it to a single stimulation form and a single maximum angular velocity. Rapid onsets could not be kept uniform. Gradual acceleration which showed the greatest individual difference was a tedious performance. The sine wave form of acceleration and deceleration is a rapid technique and affords the best guarantee against uneven starting and stopping. It is probably the best test form. If a single speed only is used, the best speed of rotation for such tests would probably be a maximum of 2° per second. That lies near the critical value. The percentages of correct responses to a continuous series of clockwise, counter-clockwise movements, and stops would furnish an unambiguous indication of the relative position of different subjects with respect to their ability to perceive and interpret rotation data. Any simple device which would give the subject's reaction time would doubtless increase the value of the test.

The implications of our threshold data with respect to direct orientation in the air may be expressed as follows:

1. Vestibular data from rotations of less than 2° per second are quite unreliable. With double that velocity judgments are often false.

2. Taking our previous study of the results of protracted rotation into consideration the vestibular problems in flying would seem to be:

(*a*) Under what conditions in the air are vestibular data sufficiently accurate to be useful?

(*b*) How may vestibular illusions of rotation be corrected or compensated?

(*c*) How may we develop, coördinate, and systematize data from the various parts of the receptor-field into the most effective control of flying under varying circumstances? These circumstances should include the temporary loss of visual data at night or in fog, as well as the illusions of vestibular and of centrifugal origin.

Plate I

The records of Plate I. represent the effort to determine whether the receptor-field for ocular nystagmus includes audition. Record 1 shows a fine nystagmus with a compensatory deviation corresponding to the rotating sound. During this record there was a subjective illusion of drifting in the opposite direction to the rotation of the sound-cage.

Record 2 shows an exaggerated coarse nystagmus that occurred in a record during which the subject reported good illusions of rotation.

Record 3 represents a series of experiments in which sound-cage rotation and moderate oscillation of the subject were coincident. It shows a certain amount of rivalry and facilitation according as the direction of actual rotation opposed or was congruent with the movements of the sound-cage. Suppression of the vestibular deviation and substitution of deviation congruent with the movements of the sound-cage are indicated by *A*. Lesser degrees of interference are indicated by *B*. Deviations apparently caused exclusively by the sound are indicated by *C*.

Plate II

Record 1 of Plate II. is the photographic record of harmonic oscillations in the form of sine curves as they were produced by the interpolation of a driving wheel and driving rod between the motor and the offset arm of the rotating platform.

Record 2 is the photographic record of arithmetical acceleration as it was produced by the interpolation of the screw-shaped driving cone and the driving wheel between the motor and the offset arm of the rotating platform. The figures at the extreme right of record 2 show the measured accelerations in degrees by two second intervals. The unit of measurement was one hundredth of a degree.

Plate III

Plate III. shows photographic records of the course of even rotation with rapid acceleration and deceleration. In both of these records the rotation indicators have been retouched to render them more legible but the general character of the rotation

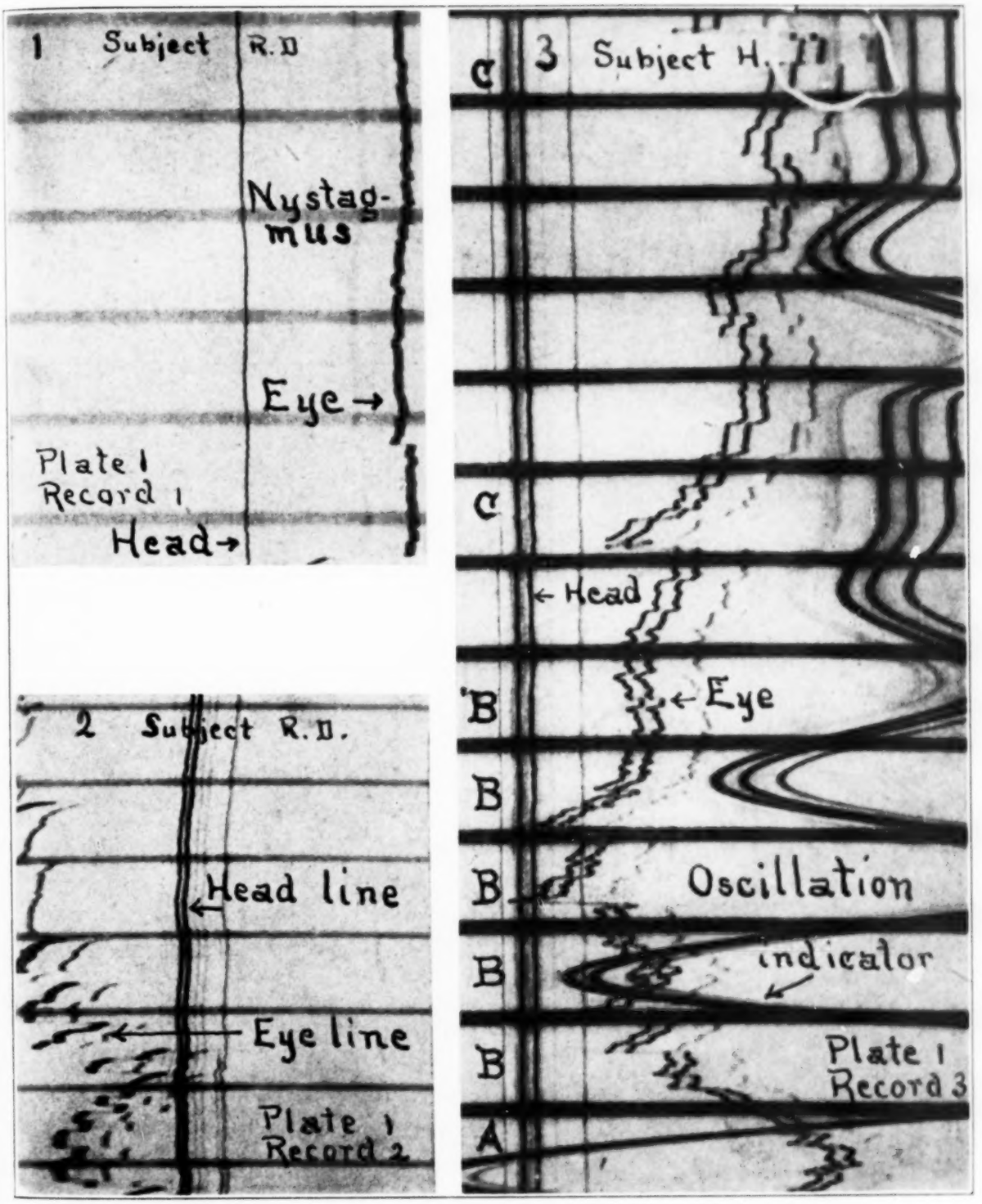
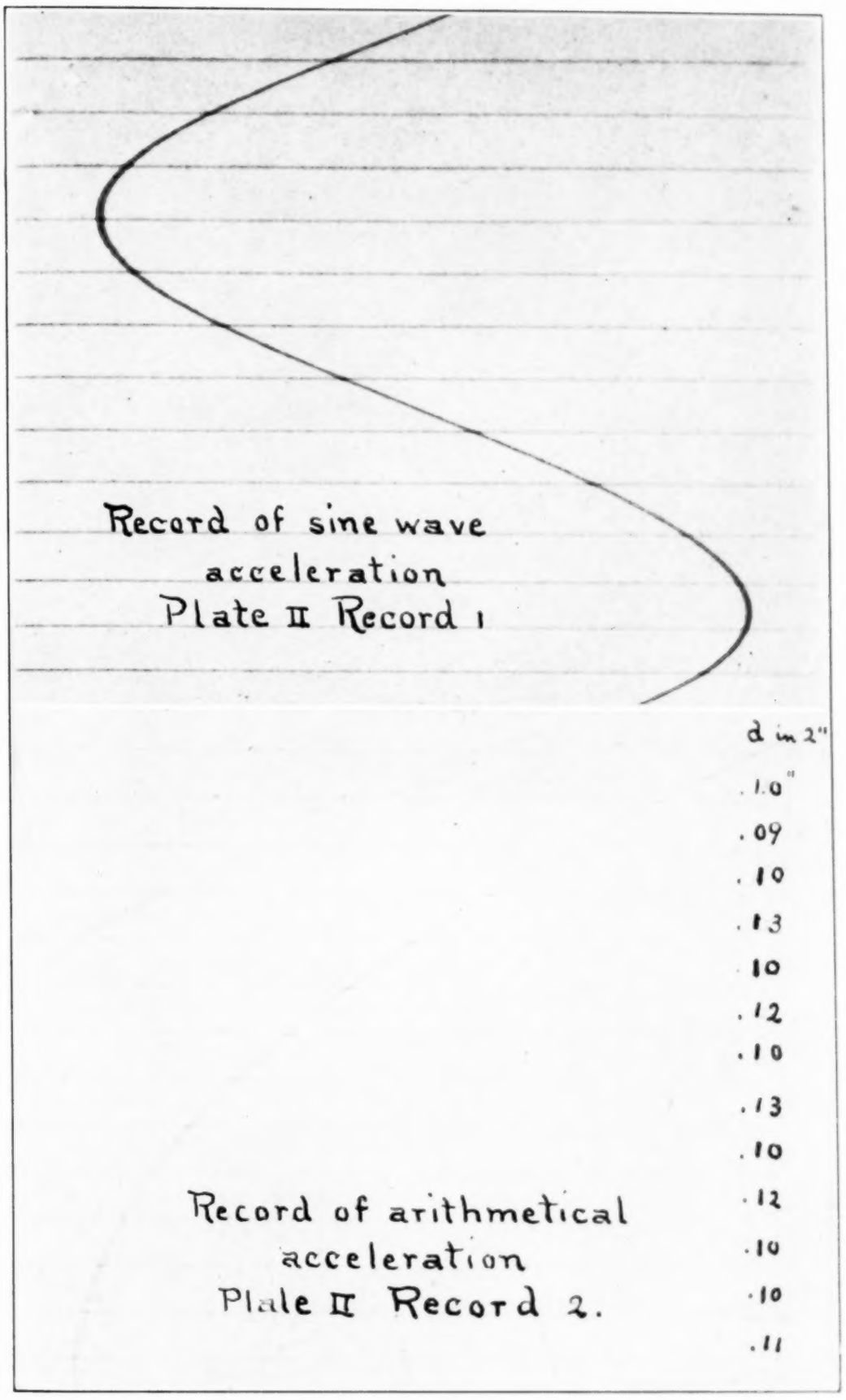


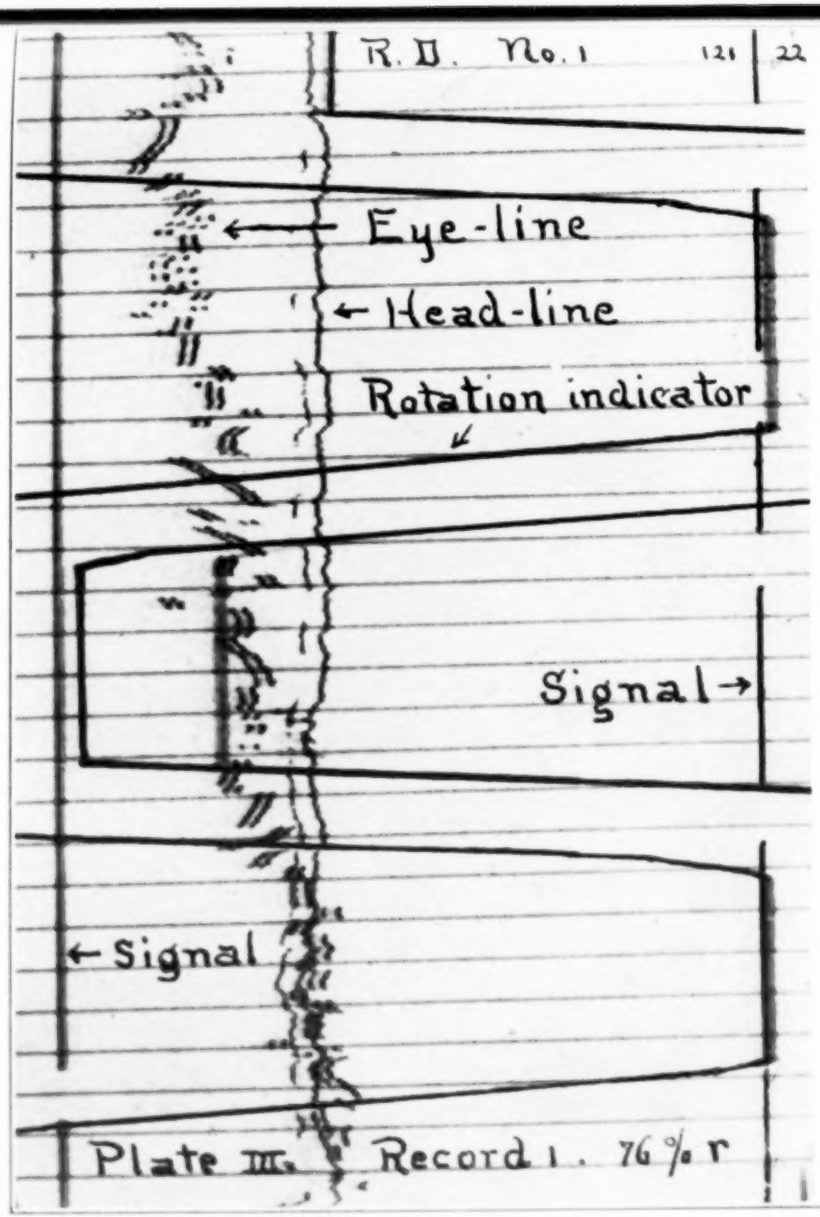
Plate I. Nystagmus produced or modified by rotating sounds.



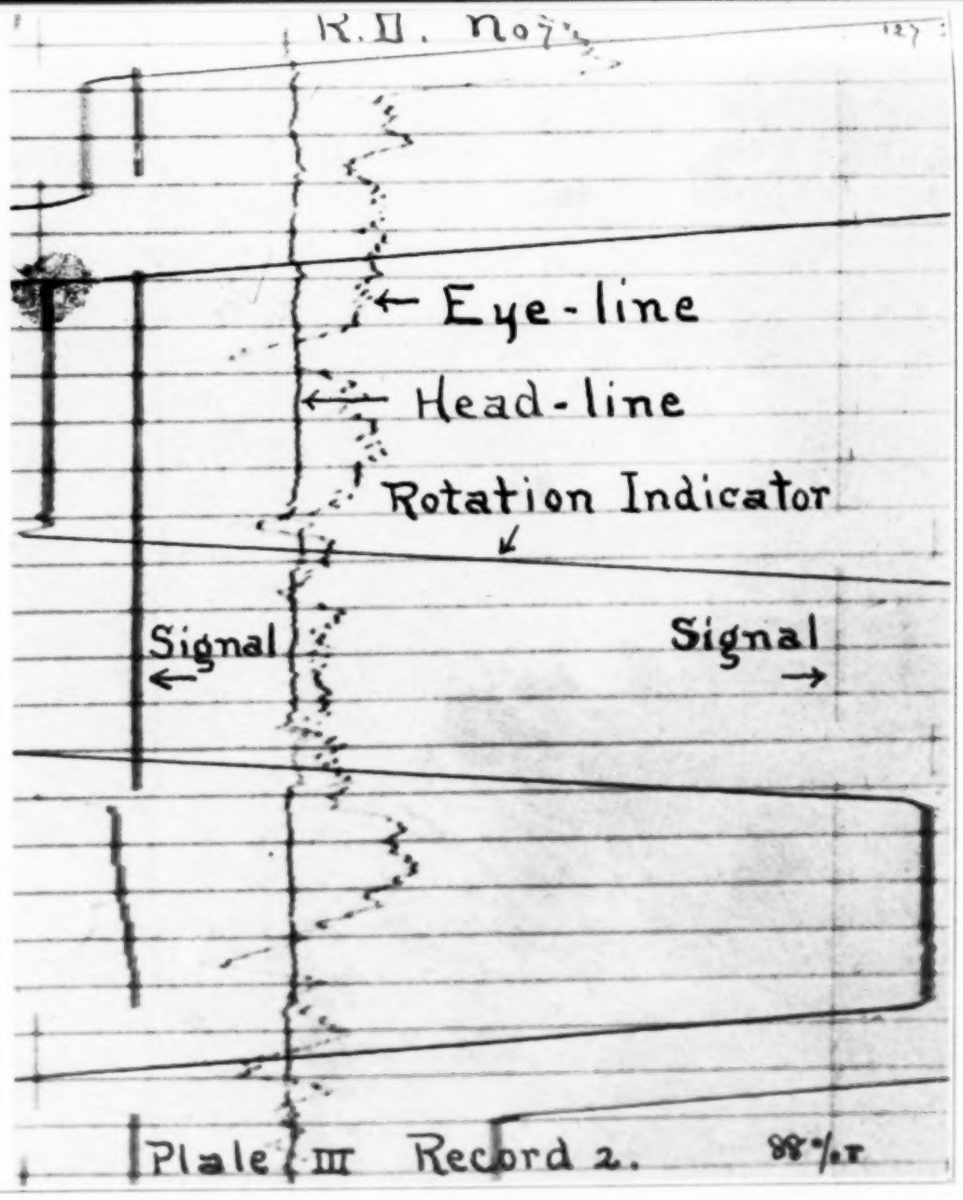
Records 1 and 2.

Plate II. Records of rotation with sine wave acceleration and with arithmetical acceleration.

R.D. No. 1 121/22 R.D. No. 1



Record 1.



Record 2.

Plate III. Records of responses to show rotation with rapid onset showing the disappearance of vestibular nystagmus after slight habituation.

and its irregularities at the moment of starting and stopping have not been altered. Second, it shows the disappearance of the compensatory nystagmus during a series of records of nearly threshold velocity.

Record 1 of Plate III. shows a series of rotations at four degrees per second. The compensatory deviations and nystagmus are clearly marked.

Record 2 is the seventh record of the series taken under similar conditions of rotation in which the compensatory deviations have either disappeared entirely or have been greatly reduced with a consequent complete change in the appearance of the eye record. It is significant that in record 2 the subjective knowledge of rotation was slightly more accurate than in record 1.

THE RELATION BETWEEN FIELD BRIGHTNESS AND THE SPEED OF RETINAL IMPRESSION

BY PERCY W. COBB

Introductory

This paper is the third of a series,[1,2] in which retinal sensitivity is investigated by means of a certain criterion, namely: by the measurement of the shortest time of exposure of a stimulus, consisting of a black dot upon a white screen, necessary in order that there may be discrimination between stimulus and no stimulus. The first communication describes the method and the investigation of the effect of certain circumstances upon the result. Among these are: the relation of threshold stimulus-time to stimulus-area; the effect of the unavoidable variables of psycho-physical experiment, such as progressive time effect (practice, fatigue) as it might influence any measurement according to its place on the program; and the effect of unavoidable fluctuations in the illumination. The second paper deals with measurements made upon a large group of subjects; it shows individual variations in sensitivity and draws correlations between these and the results of ophthalmologic examination. Both papers discuss the method as a supplementary opthalmologic test for prospective aviators.

The present work adopts the same criterion of sensitivity, and shows the effect of a wide range of variation in the illumination upon the result.

Historical

Neither the method described in this and the preceding two papers, nor any method in principle resembling it, appears, until recently, to have been used to study differential visual

[1] Cobb and Loring, Jour. Exp. Psychol., IV., 1921, pp. 175-197.

[2] Cobb, *ibid.*, V., 1922, pp. 227-246.

response, either as between individuals or as between various conditions. But the fundamental principle underlying the method, as stated and used, namely, that the product of stimulus-time and stimulus-area, other conditions equal, is constant for the threshold, is part of a more general proposition proved and used by von Kries[1] in the measurement of the minimal energy necessary to excite the eye. He refers, first, to Asher[2] who, in studying the visibility of stars, has concluded that, for the threshold, the necessary energy per second received by the eye (therefore also, brightness times angular area), is constant, provided the diameter of the stimulus is not greater than two minutes of angle in the visual field. And, second, von Kries refers to Charpentier,[3] who states that for brief exposures, not exceeding one eighth of a second, the product of brightness and stimulus time is constant for the threshold. It thus appears, as shown experimentally by von Kries, that with a given state of the eye, the least effective stimulation is conditioned by the product of brightness, angular extent and duration of the stimulus, provided certain limits of angular extent and duration are not exceeded.

It would appear also, from the more recent work of Reeves,[4] and of Pièron,[5] that there is an intensity-limit as well, for with very short times (under 5σ), both of these investigators have shown that for the threshold an actual increase of energy is necessary, that is, brightness must increase more than inversely as the time, as the latter is reduced.

The foregoing work has all dealt with positive light-stimuli; whereas the cessation of light which has been continuously falling upon the retina is in fact equally well to be reckoned as a stimulus. This sort of stimulation has had much less investigation than that consisting in the positive incidence of light. It is involved in the determination of the shortest perceptible interval between two flashes, as investi-

[1] Von Kries, *Zeitsch. f. Sinnesphys.*, XLI., 1917, pp. 373-394.

[2] Asher (*vide* von Kries, *loc. cit.*), *Zeitschrift f. Biologie*, *17*.

[3] Charpentier (*vide* von Kries, *loc. cit.*), *Arch. d'ophtalmologie*, *10*, 1890.

[4] Reeves, *Astroph. Jour.*, XLVII., 1918, pp. 144-145.

[5] Pièron, *C. R. Acad. Sci.*, *170*, 1920, pp. 525-528; *ibid.*, pp. 1203-1206.

gated by Basler[1] and by Dunlap,[2] and later by Forsythe[3] incidentally with reference to military signalling; and has been investigated for itself by Gildemeister,[4] Rutenburg[5] and and Zipkin,[6] as the shortest perceptible dark interval in an otherwise continuous flux.

The exposure-time necessary to perceive a character appearing, say, dark on a light surface as a printed letter, may perhaps fall into either class. This will be according as the surfaces seen immediately before (and after) the actual exposure are of the brightness of the dark or light parts of the stimulus pattern. In the former case, the background rises as a positive light stimulus, out of relative darkness; in the latter the character itself is a dark interval in an otherwise uniform and continuous brightness.

The latter method of presentation of stimuli has been used by Herlitzka,[7] with reference to the visual capability of the aviator; and by Ferree and Rand[8] with reference to the problems of the illuminating engineer, determining thereby what they call the 'speed of discrimination' (in fact the reciprocal of the threshold time), under various illuminations (0.4 to 12 foot candles) and for several sizes of test-object (Landolt broken rings, from 1.15 to 3.45 minutes of arc); and under various spectral lights at two different intensities.

Apparatus and Methods

For the present work, no essential change was made in the apparatus as described in the earlier communications. A new apparatus was constructed, in which the drop-frame is of metal, and descends under the influence of gravity in a pair of vertical guides made of tightly stretched piano-wire.

[1] Basler, *Arch. f. d. ges. Physiol.*, 143, 1911, pp. 245-251.

[2] Dunlap, *Psychol. Rev.*, XXII., 1915, pp. 226-250.

[3] Forsythe, *Phys. Rev.*, II. series, *16*, 1920, pp. 62-69.

[4] Gildemeister, *Zeitsch. f. Sinnesphys.*, *48*, 1914, pp. 256-267.

[5] Rutenburg, *Zeitsch. f. Sinnesphys.*, *48*, 1914, pp. 268-284.

[6] Zipkin, *Zeitsch. f. Sinnesphys.*, *49*, 1915, pp. 89-98.

[7] Herlitzka, 'Ricerche biol. sull'aviazioni (Uffici psici-fisiologici italiani dell' aviazoni militare),' Rome, 1919.

[8] Ferree and Rand, *Trans. Ill. Eng. Soc.*, XV., 1920, p. 770 and p. 777ff. Also, *ibid.*, XVII., 1922, p. 73, p. 75ff., p. 81ff.

The frame is held in its initial (uppermost) position by a small electro-magnet, and falls when the magnet is short-circuited by a key under the hand of the subject; carrying with it a small removable blind, of calculated height, which passes immediately behind the stimulus-aperture *O*, in the screen *S* (Fig. 1).

A set of such blinds was made upon the same plan as before, so that the times of exposure were a geometric series, changing by the factor $\sqrt[4]{2}$, *i.e.*, as 0.841:1 or 1: 1.189. The appropriate heights of these blinds were calculated for the series of times given by substituting the odd integral values of *T* (arbitrary stimulus-number) in the equation:

$$t = 200(1/2)^{T/8} \qquad (1)$$

A concrete idea of this relation may be derived from the following extract of the original table, giving the associated values of *T* and *t*. Other values of *t* may be obtained by remembering that eight units increase in *T* means a two-fold decrease in *t* and *vice versa*. One unit means approximately ten per cent. change in *t*, and four units mean about forty or thirty per cent. change, according as the smaller or larger *t* is the base of the percentage ($1 : \sqrt{2}$ or $1 : \sqrt{1/2}$)

T	*t*	*T*	*t*	*T*	*t*	*T*	*t*
20	35.4	22	29.7	24	25.0	26	21.0
21	32.4	23	27.3	25	22.9	27	19.3

In the present case the circular stimulus-aperture measured 0.167 inch in diameter (4.24 mm.). Its area was therefore 14.13 sq. mm., and its diameter subtended an angle of 2.43 minutes at the subject's eye, 6.01 meters away. The device for illuminating the aperture was somewhat different from the one previously used. Instead of a simple screen, at a distance back of the aperture, the image of a transilluminated milk-flashed glass was cast in the plane of the opening from behind, by means of a 10-D. trial-case spectacle lens, 20 cm. behind the opening, the milk-glass being 20 cm. beyond that in the conjugate focus of the lens. Back of this glass, at a variable distance, was a 75-watt gas-filled tungsten

filament lamp, the three (lens, glass, and lamp) being in line with the aperture and centered 1.22 m. from the floor-level. This obviated a possible defect in the earlier arrangement due to non-uniformity of illumination of the back screen, since the aperture was filled with the image of a symmetrically illuminated part of the glass, identical from whatever direction (within the cone of rays) it might be viewed. The possibility of different brightness of aperture for the two eyes was thus minimized. A moderately heavily milk-flashed glass, such as was used, may be depended upon to approximate perfect diffusion according to the cosine law, when normally illuminated and observed from angles no greater than that subtended by the interpupillary distance at 6 meters.

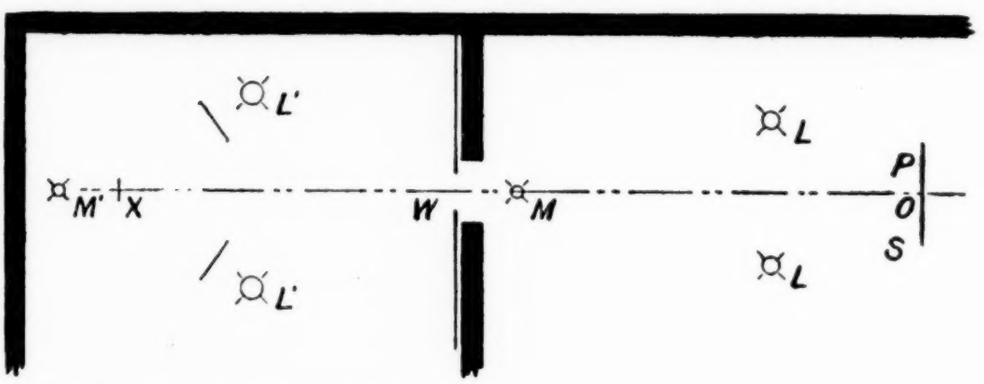


FIG. 1. General plan of the apparatus.

The subject was seated with his eyes at *X*, and saw the wall-opening (*W*) completely filled by the screen at *S*, the aperture *O* being at its center. His eyes were fixed upon the point *P*, two degrees to the left of *O*. The two lamps *L* illuminated the screen, and the two *L'* illuminated the false wall *W*, these lamps being hung at the eye-level, 1.22 m. from the floor. For the lower range of brightness the single lamps *M* and *M'* were substituted, and were hung 1.90 m. from the floor instead of at the eye-level. The apparatus for illuminating the aperture *O* was behind the screen *S*, and centered on the visual line *XO*.

The apparatus was set up in two rooms, in order that the brightness distribution in the field of vision might be better controlled. (See Fig. 1.) At a distance of 2.77 meters from the subject's eyes (at *X*) against the opposite wall of the room, a false wall of beaver board (*W*) was built and painted alabastine white. This filled a large part of the subject's visual field, extending from the floor to a height of 2.42 m.

and was 2.36 m. broad. An opening 28 x 25 cm. high whose center was 1.22 m. from the floor, was centered laterally in the false wall (at *W*), and opened into a larger, permanent, wall-opening; permitting vision of the screen (*S*) of the apparatus, measuring 76 x 61 cm., which was located in the second room at a distance of 6.01 m. from the subject's eyes. These dimensions are such that the screen more than filled the wall opening for either eye when viewed from the subject's position.

For the higher range of brightness, (*a*) the false wall was illuminated by two gas-filled tungsten filament lamps (*L'*, *L'*), hung at a filament-height of 1.22 m., symmetrically, 1.50 m. from the plane of the false wall, 1.45 m. apart. These lamps were of 1000, 500, 300, 150, and 75 watts for the five highest illuminations respectively. The screen itself was illuminated similarly by two lamps (*L*, *L*) placed on tracks, so arranged that the two lamps should subtend at the screen-center (*O*) the same angle that the first mentioned two lamps subtended at the center of the false wall. The lamps illuminating the screen were of the next specified size smaller than those in the room with the subject, except of course in the case of the smallest (75 watt) in which case the screen lamps (*L*, *L*) had to be further removed from the screen, in order that the latter should equal the false wall in brightness.

For a range of four lower illuminations (*b*), run subsequently to (*a*), the lighting had to be arranged differently. A single lamp was used to illuminate the screen (*M*, Fig. 1) and another (*M'*) of the same size in the other room to illuminate the false wall. These were hung directly over the visual line, 1.90 m. from the floor, and 2.84 m. removed (horizontally) from the screen (*S*) and false wall (*W*) respectively, which brought them 25 cm. away from the back walls of the respective rooms. The lamps used were of 500, 300, 150 and 75 watts for the four stages of illumination. The brightness of the wall in the subject's (smaller) room was found to be somewhat higher than that of the screen, and the adjustment to equality was effected by means of a rheostat of low resistance in series with the appropriate lamp.

All of the lamps used were rated at 115 and run at 110

volts. The entire set was connected on one rheostat for adjustment, and the voltage measured excluded the drop therein, but included the drop in the wiring of the apparatus, and also that in the rheostat, mentioned in the last paragraph, and that in another rheostat used with the lamp illuminating the stimulus-aperture for the purpose of affecting a color-match with the screen.

Before beginning the actual experimental work the wall and screen brightness were matched by simple visual observation from the subject's seat; then the stimulus aperture was matched with the screen with the aid of a small telescope. The photometric datum was the brightness of the central portion of the screen, measured with a Beckstein portable photometer.

The subjects, seven in number, were attached to the laboratory each in the capacity indicated in the brief description which follows. The ophthalmologic tests were conducted (except as specified) either with or without glasses, according as the subject did or did not wear correction while under experimentation.

A. A man, age 32, physiological chemist with a wide scientific interest extending into psychology. Vision: R., 20/20 + 7/9; L., 20/30 + 6/7. Wears no glasses. Angle of convergence $32\frac{1}{2}°$. Accommodation: R., 7.4 D., L., 8.85 D. Muscles at 6 meters: exophoria $2\frac{1}{2}^{\Delta}$; left hyperphoria $\frac{1}{2}^{\Delta}$; prism divergence $6\frac{1}{2}^{\Delta}$.

B. A woman, age 34, biologist. Glasses, for close work only, R. and L., + 0.5 D. sphere, is not used in experiment. Vision: R. and L., 20/30 + 4/7. Angle of convergence 32 $\frac{1}{2}°$. Accommodation: R., 9.25 D.; L., 7.4 D. Muscles: right eye moves possibly less than normal when vision is directed up and right. Left eye breaks in extreme convergence. At 6 meters, esophoria 4^{Δ}, prism divergence 7^{Δ}.

C. A man, age 31, physicist. Vision, *sans* glasses: R., 20/80 + 1/4; L., 20/80 + 3/4. Wears correction: R., −0.12 sph., −1.12 cyl., ax. 180°; L., −0.87 sph., −0.25 cyl., ax. 180°. Vision, with correction: R., 20/40 + 2/5; L., 20/30 + 3/7. Angle of convergence 30°. Accommodation: R., 8.0 D.;

L., 8.3 D. Muscles: left eye breaks in strong convergence. At 6 meters, exophoria $3\frac{1}{2}^{\Delta}$, right hyperphoria 4^{Δ}, prism divergence 8^{Δ}.

I. A man, age 37, glass blower, employed in special work accessory to research. Wears no correction. Vision: R and L, 20/30 + 4/7. Angle of convergence $40\frac{1}{2}°$. Accommodation: R., 7.1 D., L., 8.7 D. Muscles, at 6 meters: esophoria 2^{Δ}, right hyperphoria $\frac{1}{2}^{\Delta}$, prism divergence 12^{Δ}.

L. A man, age 45, biologist. Vision, without glasses; R., 20/40 + 1/6; L., 20/60 + 2/5. Wears corection: R. and L., −1.00 sph.; which gives vision: R., 20/30 + 4/7; L., 20/20 + 3/7. Angle of convergence $22\frac{1}{2}°$. Accommodation: R., 6.7 D.; L., 7.8 D. Muscles, at 6 meters: exophoria $\frac{1}{2}^{\Delta}$, right hyperphoria 1^{Δ}, prism divergence 4^{Δ}.

S. A woman, age 24, research assistant in physics. Wears no glasses. Vision: R., 20/20 + 1/9; L., 20/15. Angle of convergence 35°. Accommodation: R., 10.2 D.; L., 10.3 D. Muscles at 6 meters: lateral orthophoria, right hyperphoria $\frac{1}{2}^{\Delta}$, prism divergence $6\frac{1}{2}^{\Delta}$.

T. A man, age 29, physicist. Vision, without glasses: R., 12/200; L., 12/200. Wears correction: R. and L., −2.00 sph. Vision with correction: R., 20/20 + 7/9; L., 20/20 + 8/9. Angle of convergence $40\frac{1}{2}°$. Accommodation: R., 9.9 D.; L., 11.1 D. Muscles at 6 meters: exophoria 9^{Δ}, right hyperphoria 2^{Δ}, prism divergence $12\frac{1}{2}^{\Delta}$.

Nine different illuminations were used. The corresponding brightnesses of field were: in the upper range (*a*), five stages differing by a factor of approximately two, from 342 candles per sq. meter (107 millilamberts) to 24.8 c. per sq. m. (7.8 ml); and in the lower range (*b*), four stages from 31.3 to 3.33 c. per sq. m. (9.83 to 1.05 ml.). Corresponding series were run with both wall and screen illuminated (*L*) and with screen only (*D*), the lamps in the subject's room being turned off. In the latter case, the subject's visual field was dark except for the area of the screen seen thru the wall-opening, subtending at his eyes 5.8° horizontally and 5.2° vertically. In the case of the *L* series, the white false wall was made as nearly as possible equal in brightness to the screen at the

margin of the aperture. Its area subtended horizontally 46.6°, vertically 47.6° at the subject's eyes. The rest of the room, finished in moderately light oak and yellowish-tan paint of somewhat higher reflecting power, filled the outer parts of the visual field and was free from specular reflection from the subject's viewpoint. The relative unimportance of the extreme outlying portions of the visual field under these circumstances will appear from the results.

Paper screens were used where necessary to protect the subject's eyes from direct light, and these did not exceed the rest of the field in brightness. All of the experiments were conducted binocularly, with fixation upon a black spot 1 cm. in diameter, situated on the screen 21 cm. to the left of the stimulus aperture. This was 2° to the left in the visual field. Four series were run each day with each subject in the order *L*, *D*, *D*, *L* or *D*, *L*, *L*, *D* alternately for each brightness. The various levels of brightness were so varied as to be each represented fairly over the whole course of experimentation.

Before each exposure, a 'ready' signal was given the subject by a small buzzer. He released the drop by a key under his right hand, and announced his judgment by means of a buzzer key under his left hand, the signals being: three for 'stimulus present,' and two for 'absent.'

The method of serial groups was used as before and has thoroly justified itself. This method consists in giving a number of equal stimuli mixed with a number of blanks (five of each in the present case); first, using stimuli of such magnitude that all ten of the group are correctly called by the subject; then proceeding at once with a similar group, using a stimulus one stage (two units of *T*, or as 1 : 0.841) shorter in time; and so on until a group was reached in which the subject failed completely to differentiate between stimuli and blanks. This occured when his right answers ceased to exceed the wrong answers in number, or what is exactly the same, when the rightly-called stimuli ceased to exceed the wrongly-called blanks. This concluded one series.

Each group within a series was scored, the score being

the excess of right over wrong answers on the basis of 10, or the excess of right answers to stimuli over wrong answers to blanks on the basis of five. The two scores are identical, altho the latter method was the one actually used in computing them. Thus from any series a set of scores was derived, corresponding to a series of values of T, from which a numerical threshold could be computed.

The method of computation for the threshold was slightly different from the one previously used: instead of interpolating in the series for the value of T at which 50 per cent. discrimination between stimulus and blank took place, as before, the point was found such that the 'crossed judgments' were equal in number; that is, such that the failures on the large-stimulus side of this point were equal in number to the successes on the small-stimulus side. Interpolation for this point was possible by assuming the net successes (or failures) at any stimulus to be distributed uniformly over the two adjacent half-intervals. There are theoretic objections to this procedure, but these are outweighed by the fact that, for two subjects, the final mean T's obtained by the two methods of computation were only insignificantly different (see Table I.), while by the second method the mean variations were somewhat smaller in both cases; no doubt for the reason that by this method no single judgment is without effect upon the computed threshold, as it may be in the first.

Results

Table I. gives average results for subjects A and B in terms of the stimulus numbers, computed from the several series (α) by interpolation for the 50 per cent. frequency point, (β) by interpolation for the point of equal crossed judgments, and (γ) in the case of subject A, with a correction for practice effect. This subject alone, when his results were compared from day to day, showed a progressive increase in sensitivity for the first ten days, with no subsequent systematic time-change.[1] The results of the others were examined

[1] For subject A, the closest fitting straight line that could be fitted to the plot of his daily relative means for the first ten days showed the relative mean to rise from 0.841 to 1.041, the total rise being 0.200; and the subsequent approach to constancy

in the same way, without showing any such change. Previous work has indicated that threshold measurements made in this way do not in general show such progressive time-effects.

In order to estimate such incidental effects, it was convenient to express all threshold values in terms of the means. Accordingly for each group of series, representing identical conditions, each threshold value (T) was divided by the mean T for the group. The relative results, so obtained, could be intercompared as to accidental variability between one condition and another where the means were different, and were conveniently used in computing a general relative mean variation. These are the mean variations stated in the last row of Table I., for all thresholds represented in the respective columns.

TABLE I

Brightness		*A*			*B*	
C. per Sq. M.	Ml.	α	β	γ	α	β
342.....	107	40.01	40.10	41.39	31.46	31.44
201.....	63.1	39.50	39.48	41.04	30.07	30.12
105.....	33.0	36.69	36.56	38.44	30.05	29.95
51.6.....	16.2	34.63	34.96	36.58	27.19	27.42
24.8.....	7.8	32.35	32.34	33.50	25.10	25.30
General mean....	.....	36.64	36.69	38.19	28.77	28.85
Mean var'n, relative..	.....	0.060	0.058	0.030	0.036	0.034

I. Comparative results of different methods of computation, expressed in stimulus number T, subjects A and B:

(α) computed by interpolating the point in the series of 50 per cent. net right answers.

(β) by equalizing the crossed judgments; *i.e.*, finding a point such that the wrong answers above it are equal in number to the right answers below.

(γ) for subject A, by using method (β) and correcting the early values for lack of practice.

The 'Mean Variation, Relative' is derived from the results of the separate series, not from the values standing above in the table.

at 1.041 was about as close as the approach to straight-line increase before. The mean T, corresponding to unity in these terms, for all brightnesses in range (a) was 36.69 (Table IV., A'), the relative value 1.041 corresponding to the corrected mean, 38.19 (Table IV., A). In stimulus number the progressive rise during the ten days was therefore on the average, 0.200 x 36.69 or 7.34 units, corresponding to a decrease in time as 1: 0.53.

TABLE II

Brightness		A		B		C		I		L		S		T	
Candles per sq. m.	Ml.	L	D	L	D	L	D	L	D	L	D	L	D	L	D
(a) UPPER RANGE OF BRIGHTNESS															
342	107	5.58	5.51	13.7	12.6	14.8	17.5	7.26	8.91	14.2	13.5	8.45	7.87	22.4	22.2
201	63.1	5.69	5.74	14.3	15.2	16.3	20.5	9.23	11.0	14.4	14.5	8.45	8.75	25.2	29.4
105	33.0	7.36	6.97	15.7	14.2	20.5	22.2	11.0	12.6	15.8	15.6	9.84	9.75	23.5	22.8
51.6	16.2	8.22	8.59	19.1	18.1	20.2	24.3	16.4	14.0	20.0	17.8	11.2	10.7	28.0	31.0
24.8	7.79	11.2	10.7	22.0	22.6	28.0	28.2	20.2	21.0	24.4	24.6	14.2	14.1	47.3	45.8
(b) LOWER RANGE OF BRIGHTNESS															
31.3	9.83	9.62	9.06					16.1	18.8			12.7	12.1		
18.9	5.95	11.6	11.2					19.8	22.5			13.8	14.0		
7.73	2.43	17.7	18.3					29.8	37.9			22.7	21.2		
3.33	1.05	30.3	27.5					53.5	62.8			33.1	33.3		

II. The time of darkening of a circular spot 4.24 mm. in diameter, at 6.01 meters distance, necessary in order that a threshold impression may result. Seven subjects, *A*, *B*, *C*, *I*, *L*, *S* and *T*. The sub-heading *L* means: extensive bright surroundings (46.6 x 47.6° in the visual field); the sub-heading *D*, bright surroundings restricted (5.8 x 5.2°), the remainder being dark.

Brightness is stated in candles per square meter and in millilamberts; and the fields indicated by *L* and *D* were kept as nearly as possible uniform with the area about the stimulus aperture.

The times are given in thousandths of a second (σ). The reciprocals of these are plotted in Fig. 1.

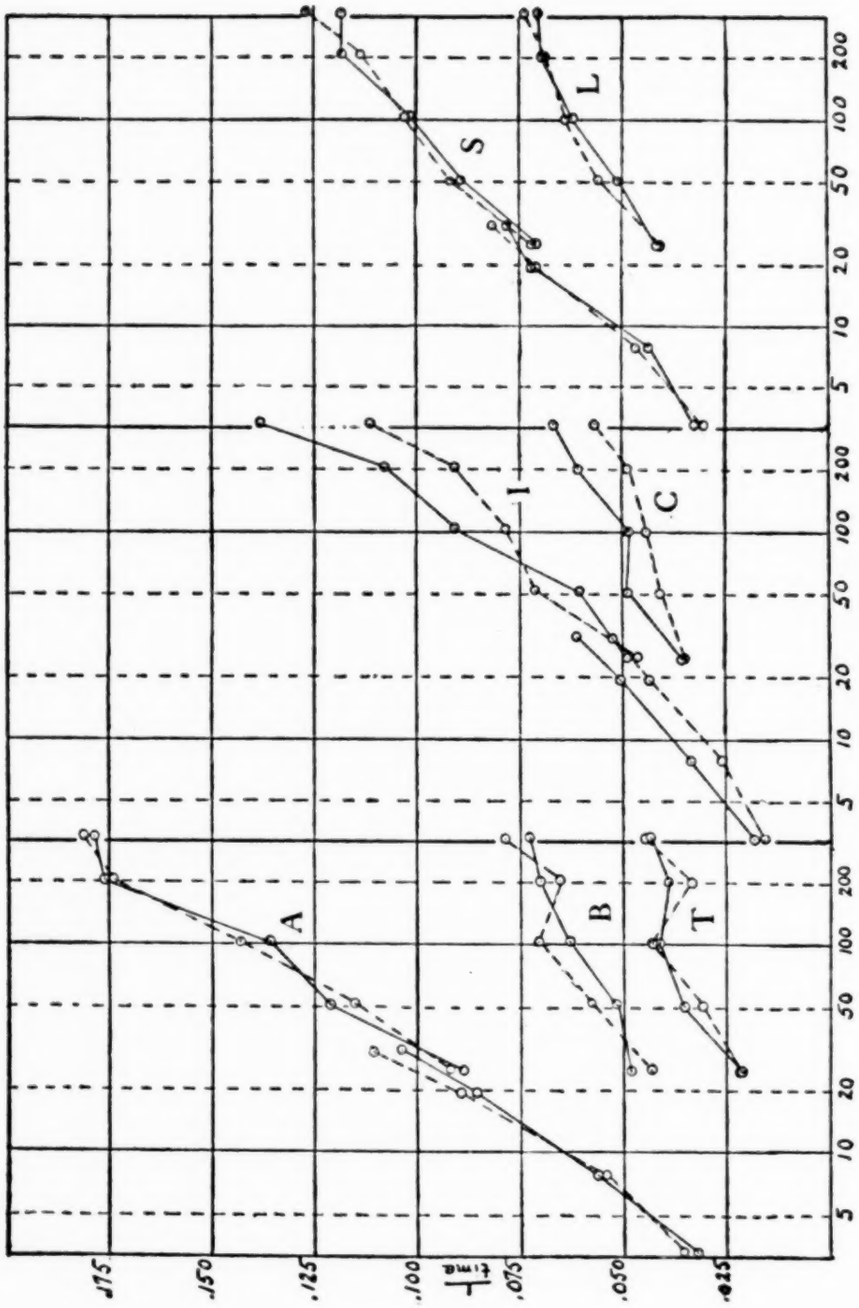


FIG. 2. Reciprocals of threshold times given in Table II., for each subject, plotted against the logarithm of the brightness.

——— solid lines, 'light' series (*L*).
– – – – – – broken lines, 'dark' series (*D*).

It will be seen that the two methods of computation (α, β in the table) gave almost identical averages, and mean variations which differ almost insignificantly in favor of choice of the second method. The effect of the correction for practice is shown in Table I., for subject *A*, by the comparison on the columns headed β and γ. Altho all his average values were increased somewhat by this procedure there is no difference in the trend of the results. In what follows, the corrected values (γ) are used for *A*, while the other results were simply computed by the method β.

Table II., gives the average thresholds stated in thousandths of a second for all subjects and all brightnesses used. In Fig. 2, the results are plotted, not as times, but as reciprocals of times (relative 'speeds') against the logarithms of the brightnesses. Fig. 3 shows the same, for the

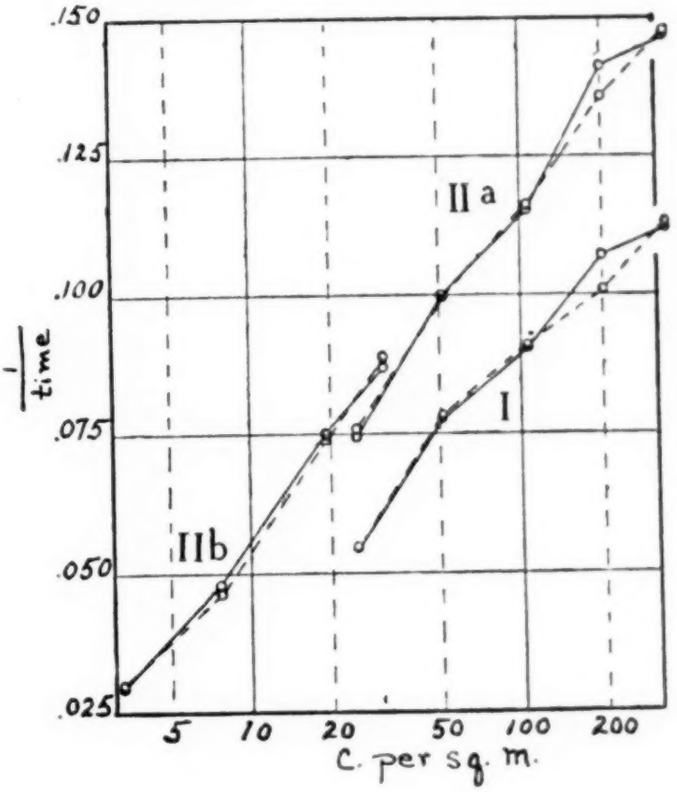


FIG. 3. Reciprocal of weighted mean threshold time, as given in Table III., 1/*t* plotted against the logarithm of the brightness.

Curve I., seven subjects.

Curves II., for subjects *A*, *I*, and *S* in high (*a*) and low (*b*) ranges of brightness as in Table III.

———————— solid lines, 'light' series (*L*).

– – – – – – – – broken lines, 'dark' series (*D*).

weighted mean results for all subjects. The weights assigned the several subjects (p, Table IV.) for computing these means are proportional (1) directly to the whole number of series and (2) inversely to the square of the subject's general relative mean variation. The quantities averaged are the values of T, which are logarithmic (rather, cologarithmic) in their relation to the time. Hence the time computed from the average T is a geometric mean.

The values of $1/t$ plotted in Fig. 3 are included in Table III. as well as the mean values of t.

TABLE III

WEIGHTED MEAN TIMES FOR SUBJECTS *A*, *I*, AND *S*

(*a*)

C. per Sq. M.	MI	t			$1/t$		
		L	*D*	*M*	*L*	*D*	*M*
342.....	107	6.79	6.82	6.80	.147	.148	.148
201.....	63.1	7.08	7.38	7.23	.141	.136	.138
105.....	33.0	8.71	8.61	8.66	.115	.116	.116
51.5....	16.2	9.95	10.05	10.0	.100	.0996	.0998
24.8....	7.8	13.4	13.2	13.3	.0748	.0760	.0754
(*b*)							
31.3....	9.83	11.5	11.2	11.4	.0867	.0889	.0878
18.9....	5.95	13.3	13.5	13.4	.0750	.0741	.0746
7.73 ...	2.43	20.9	21.5	21.2	.0478	.0466	.0472
3.33 ...	1.05	34.0	33.3	33.6	.0294	.0301	.0298
WEIGHTED MEAN TIMES FOR SEVEN SUBJECTS							
342.....	107	8.9	8.8	8.8	.112	.113	.112
201.....	63.1	9.4	9.9	9.6	.107	.101	.104
105.....	33.0	11.1	10.9	11.0	.0904	.0916	.0910
51.6....	16.2	12.9	12.8	12.8	.0776	.0782	.0779
24.8....	7.8	16.9	16.8	16.8	.0592	.0594	.0593

III. The geometric means (t, in σ), of the values given in Table II. for various illuminations, and their reciprocals, the corresponding 'speeds.' For the method of weighting see Table IV. and text. *L* and *D*, same as in Table II.; *M*, mean of *L* and *D*. The values of $1/t$ are those plotted in Fig. 2.

DISCUSSION

In the selection of $1/t$ and the logarithm of the brightness for plotting in Figs. 2 and 3, the primary consideration was that this relation was the most nearly linear of those that were tried. When $1/t^2$ was used the results of the seven

TABLE IV

AVERAGE T AND MV FOR EACH SUBJECT

(a)

	N	Mean T	MV, rel.	MV_T	t,σ	p
A.....	100	38.19	0.0296	1.13	7.3	13
A'	(100)	(36.69)	(0.0583)	(2.14)	(8.3)	—
S.....	100	34.43	0.0296	1.02	10.1	13
I.....	88	32.34	0.0384	1.24	12.1	7
B.....	84	28.84	0.0344	.99	16.4	8
L.....	88	28.40	0.0415	1.18	17.1	6
C.....	100	26.10	0.0748	1.95	20.8	2
T.....	84	22.42	0.0972	2.18	28.7	1

(b)

A.....	80	29.65	0.0333	.99	15.3	10
S.....	80	27.26	0.0422	1.15	18.8	8
I.....	80	22.28	0.0772	1.72	29.0	3

IV. The means for the several subjects: (a) for the upper range of brightness (342 to 24.8 c. per sq. meter); (b) for the lower range (31.3 to 3.33).

N—number of series involved.

T—values in scale-number.

MV, rel.—mean variation as a fraction of mean T.

MV_T—mean variation in terms of same units as T.

t, σ—time in thousandths of a second corresponding to T.

p—weight assigned each subject for computing values given in Table III. and plotted in Fig. 2.

The values for subject *A*, uncorrected for practice, are given in parentheses opposite *A'*.

The three weights under (b) are computed from the combined (a) and (b) results for the three subjects *A*, *S*, and *I*.

subjects, over the higher range, (a), gave a more nearly straight line than they show in Fig. 3, I; while the results for the three (II.a and II.b) showed a pronounced curvature, with diminishing slope at low brightness. It would be natural to expect that Fig. 3 plotted as it is would show a similar characteristic if the observations had been carried to low brightness approaching that of total invisibility of the stimulus. This would certainly occur at some point, where t would theoretically become infinite and $1/t$ equal to zero, and it is scarcely to be expected that this would show as a clean intersection of a straight line with the x-axis, but rather that the slope would diminish and the line join the axis at

an indefinite point, forming a 'toe.'[1] Again, it is certain that were the brightness increased sufficiently (to the point of dazzle) visibility would again go to zero. That is, the curve would rise to a maximum, and fall again to the x-axis, the rising portion presumably departing from the value zero slowly, and approaching the maximum slowly. There are slight indications in Fig. 3 which we may well interpret as real tendencies of the curve toward a less slope above and below, and if the course of the complete curve is as suspected, certain parts of the ascent could be selected in which $1/t^2$ or $1/\sqrt{t}$ might show a more nearly linear rise than $1/t$ does in the present case. What has just been said of Curve I., Fig. 3, may be a case in point. However, it is approximately true, as far as these results show, that

$$1/t = k \log B/B_0, \qquad (2)$$

where B is the brightness, and k and B_0 are constant. The range of brightness to which this applies covers that in use in artificial illumination practice where fine visual discrimination is at all an object, say from 3.3 to 340 c. per sq. m. (1 to 107 ml.)

While the relation stated above holds fairly well for the mean threshold, examination of the individual results (Fig. 2) shows indications of both the upper (subjects L and T, possibly also S and A) and the lower (subject I, possibly C) deviations from this relation just spoken of; and the extremely

[1] This opinion is based on the results obtained by other visual criteria, when the observations are carried to low brightness. (1) The number of least perceptible brightness differences represented as a function of the logarithm of the brightness, increases slowly at low brightness, and more rapidly (nearly linearly) as the brightness in increased. That is $\triangle B/B$ is first large, then diminishes (Koenig, Gesammelte Abhandlungen, Leipzig, 1903, pp. 116-134 and 135-139). (2) Visual acuity, as a function of the logarithm of the brightness undergoes a slower change at low brightness (*ibid.*, pp. 378-395). (3) Experiments with the sectored disc, show that the critical flicker-frequency (which will be shown later is a function similar to 'speed' as understood here), as a function of the logarithm of the brightness, falls off less rapidly at low brightness than at high. (Porter, *Proc. Roy. Soc.*, *A*, *86*, p. 496 ff.)

In the second and third instances, just mentioned, the change in mode is somewhat abrupt, and the difference has been referred to the change from rod to cone function. In the case of the least perceptible brightness, however, the change is not abrupt, the value of $\triangle B/B$ increasing from a minimum at first slowly, then more rapidly as the brightness level is reduced.

long time required by *I* at the very lowest intensity (53.5 and 62.8σ, Table II.) is in harmony with the curvature shown in his individual plot.

The dotted lines in Figs. 2 and 3 show the result of darkening the field of vision (the *D* series), except the exposed area of the screen, measuring 5.8 x 5.2°. The individuals are various in their behavior with respect to this change, and in general are not consistent with themselves. In the average results, the greatest difference (0.66 in *T*, less than 6 per cent. in time) is at the brightness of 201 c. per sq. m. (63.1 ml.) where the weighted mean thresholds (*T*) and their probable errors are as follows:

$$\begin{aligned} L&: 35.31 \pm 0.18 \\ D&: 34.65 \pm 0.18 \\ \text{Diff.}&: 0.66 \pm 0.25 \end{aligned}$$

The difference is thus 2.6 times its probable error. According to the probability tables, a difference such as this, or greater, may result from pure chance as often as once in 12 or 13 times. Since all the other differences shown in Fig. 3 are not only much smaller than this but diverse in direction, we may conclude that darkening the visual field beyond a radius of 2 1/2 to 3 1/2° from the point of stimulation has not consistently affected the result.

There is a possible explanation for the diverse results in this respect as well as for the more general irregularities shown in Fig. 2, in the behavior of the pupil. At higher brightness the pupil, altho it compensates with adaptation toward a mean width, is certainly, on the average, somewhat smaller than at lower brightness. This will have a first effect of reducing the effective intensity-ratio, as between any two conditions. If the brightnesses are, say, as 10 to 1, with a smaller pupil in the former the ratio of the actual illuminations upon the retina will be something less than this, by the factor of reduction in pupillary area. This should have no more effect upon the results than a moderate distortion of the scale of brightness.

However, the pupil has a dioptric effect presumably the

more in evidence the less perfect the refractive apparatus of the eye, that is, the larger the diffusion circle upon the retina. There is no way of knowing in any particular case whether definition will be increased or diminished by the addition of an annular zone about a central one, such as takes place when the pupil widens. The result will depend upon the perfectness of each zone in itself, and whether the two have a common focus. Irregular variations may thus be introduced by pupillary changes: primarily, as the general level of stimulation is high or low; and secondarily, when a large part of the brightness in the outlying parts of the field is removed, as in series *D*. Such variations, if they are thus to be explained, must depend upon the retinal area over which the stimulus is distributed, since the total energy ('negative' energy in the present case) of the stimulus is independent of the area. In an earlier paper it was shown by the present method that the threshold was determinable in terms of energy, within certain limits independently of the area of stimulation, other conditions being the same. In view of this fact it would seem improbable that minute changes in the definition due to small differences in the size of the pupil would be responsible for the irregularities in question, the more so, as such irregularities seem to correlate better with the mean variations of *T* for the respective subjects than with their vision as measured by the letter chart.

The question has been raised whether in the present case, the 'negative' stimulus gives the same result that a 'positive' one, of the same numerical value, would give. If we designate the screen-brightness by *B*, the negative stimulus brightness will be zero. The positive brightness, of equal numerical value, would be $2B$, the stimulus-value being the difference $B - 0$ or $2B - B$ as the case may be. No other assumption than this will answer. The stimulus must be the difference in brightness between stimulus-area and ground, since this difference is zero in the fore-exposure before the aperture is darkened (or illuminated), that is, when no stimulus is present, and this difference is the effective thing in making the dot visible in either case.

It would seem to follow from the Talbot-Plateau law, that the positive and negative stimuli, as defined above, would give identical results, except, of course, that the subject would see a bright instead of a black dot upon the screen.

In its general form, the Talbot-Plateau law states that a regularly intermittent brightness is effective as a constant brightness equal to its time-weighted mean, when the cycle of intermittence is so brief that no flicker is seen. Mathematically stated:

$$B_m = \frac{\Sigma B\, dt}{\Sigma dt};$$

or for a special case:

$$B_m = \frac{B_1 t_1 + B_2 t_2}{t_1 + t_2}, \qquad (3)$$

where B_m is the brightness of a constant field which has an effect the same as the intermittent one above the flicker speed; B_1 and B_2 are the constant brightnesses of the intermittent field effective during the times t_1 and t_2 respectively; t_1/t_2 is constant and $t_1 + t_2$ is the whole period of the cycle of intermittence. This statement may apply to a sectored disc where B_1 is the 'open' brightness, B_2 equals zero and t_1/t_2 is the ratio of open to closed sector.

At a high rate of intermittence such a field is constant in appearance and is not to be distinguished from a constant field of brightness B_m. If the speed of intermittence is reduced, at a certain rate a slight flicker appears; but the disc at this rate undergoes no progressive change in appearance more than does the field B_m. The flicker must be interpreted as due to slight oscillations in the sensory apparatus, due to B_1 and B_2, greater and less respectively than B_m, and acting during the times t_1 and t_2. Of these hypothetical oscillations we can say definitely that they are equal in amplitude and opposite in direction since there is no progressive change in the appearance of the intermittent field. The mean rates of change under the influence of B_1 and B_2 must

be therefore inversely as t_1 and t_2, since equal changes are taking place in these times. But from (1) above:

$$B_1 - B_m = (B_1 - B_2)\frac{t_2}{t_1 + t_2}$$

and

$$B_m - B_2 = (B_1 - B_2)\frac{t_1}{t_1 + t_2},$$

from which

$$(B_1 - B_m) : (B_m - B_2) = t_2 : t_1 = 1/t_1 : 1/t_2;$$

and since the two oscillatory changes are in the opposite direction we have the two rates of change, with their appropriate signs, proportional to $(B_1 - B_m)$ and $(B_2 - B_m)$. Or, stated generally: the rate at which a minimal displacement of sensory equilibrium takes place is proportional to the disturbing brightness minus the adaptive brightness with which the retinal elements are initially in equilibrium. If experiment such as that herein described should show that two stimuli of brightness 0 and $2B$, with adaptation to B, are of threshold effectiveness in unequal times, it would seem to prove that a disturbance in one direction is not equally effective with an equal one in the opposite direction, which would be definitely out of harmony with the well established Talbot-Plateau law.[1]

In a recent summary of the laws of the critical flicker frequency for intermittent visual stimulation Ives[2] states

[1]This conclusion might at first appear contradictory to the results of Rutenburg (*loc. cit.*). His comparison was between the shortest perceptible flash, and the shortest perceptible dark interval, for the same brightness and field-area, the order of experimentation being (*a*) dark-bright-dark, and (*b*) bright-dark-bright, and he found for equal threshold duration of bright (*a*) and dark (*b*), that the brightness had to be 2 to 5 times as great in the latter case, *i.e.*, for equal brightness the threshold 'pause' was longer than the threshold 'flash.' It is not difficult to see that the subject was relatively light-adapted for the pause, and dark-adapted for the flash, so the brightness of the latter was relatively higher than, even tho physically equal to, the brightness preceding and following the pause. According to Rutenburg the difference appears at the high levels of brightness, and tends to disappear at lower levels, which is in accord with the fact that the corresponding adaptation-difference tends also to be less at low brightness.

[2]Ives, *Jour. Opt. Soc. Am.*, VI., 1922, p. 343 ff.

that 'for all wave forms, critical frequencies plot against the logarithm of the illumination as parallel straight lines' and that 'if the flicker range is varied, the range factor (amplitude) enters as a multiplier of the illumination'; expressing these facts in an equation:

$$\omega = a' + b' \log I\alpha;$$

where ω is the critical speed in cycles per second, I the illumination, α the amplitude and a' and b' are constants.

Obviously ω is the 'speed,' that is, the reciprocal of the cycle-time, proportional to the reciprocal of the time of any stated part of the given cycle; and proportional therefore to $1/t$ of the present paper. In the case of the present work, the illumination is proportional to B (the screen brightness), and the amplitude *is* B, whence we have by substitution:

$$1/t \propto a' + b' (\log cB + \log B).$$

This readily reduces to the form:

$$1/t = k \log B/B_0,$$

which has already been derived from the experimental data of the present paper. The present results are therefore in good agreement with the law of intermittent vision.

Summary

1. A method previously used is applied to the investigation of the speed of retinal response as a function of field brightness and brightness distribution.

2. Seven subjects were used. These showed rather large individual variations in sensitivity, and somewhat different variations with the changes in illumination and distribution of light in the visual field.

3. When the stimulus occupied the center of an area subtending 5.8 x 5.2° in the visual field, of stated brightness, the average results were not different from those obtained when the bright field was enlarged to include 47° horizontally and vertically. The subjects used did, however, show individual differences in this respect.

4. In general, if t represent the threshold time of stimulation, and B the brightness of the experimental field, the relation followed an equation of the form:

$$1/t = k \log B/B_0,$$

where k and B_0 are constants depending upon the individual and upon other experimental conditions, notably upon the solid angle subtended by the stimulus-spot at the eye of the subject.

5. This mathematical statement is in good agreement, as to form at least, with the laws governing critical flicker-frequency for intermittent stimulation.

NELA RESEARCH LABORATORIES,
CLEVELAND OHIO,
NOV., 1922.

THE VARIABILITY OF AN INDIVIDUAL IN REPETITIONS OF THE SAME TASK[1]

BY E. L. THORNDIKE

Institute of Educational Research
Teachers College

If an individual is tested repeatedly with a mental task, such as repeating a list of digits heard, or reacting to a signal, or taking alternative forms of an intelligence examination, and if allowance is made for any practice effect, one might expect that his varying performances would show a distribution like that of Fig. 1, departing farther downward than

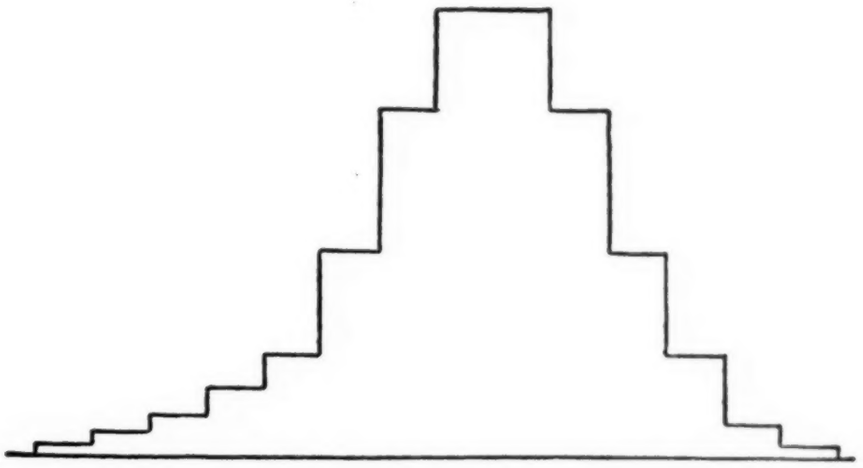


FIG. 1.

upward from his modal performance. One might expect this because there seem to be, at least as possibilities, certain potent causes producing variations downward which are unmatched by equally potent causes producing variations upward. In series of very small tasks, such as single reactions or repetitions of lists of digits or words, such a skewness is found. A person who as a rule can repeat an eight digit series may by reason of inattention or other disturbance

[1] This is one of a series of investigations made possible by a grant from the Carnegie Corporation.

score zero, failing to remember any two digits in their proper positions, tho he never succeeds in scoring sixteen. It is a common opinion that states of discomfort, nervousness, confusion, and such ill defined conditions of incapacity as 'being stale,' 'having an off day,' 'not being myself at all,' and the like, produce a similar effect upon longer and varied tasks or collections of tasks, such as school examinations or intelligence tests.

Since the matter has a very important bearing upon certain problems in the theory of measurements, as well as being of importance in the practice of testing and examining, I have studied the facts in the case of three representative tasks, namely, a 30-minute test in reading paragraphs and answering questions about them, Army Alpha, and Part I of the Thorndike Intelligence Examination for High School Graduates. The general result is that if such excessive downward displacements occur at all during ordinary conditions of health, they are so rare as to be almost negligible. The variations of an individual are as a rule distributed symmetrically about his central tendency as shown in Fig. 2, not in the form of

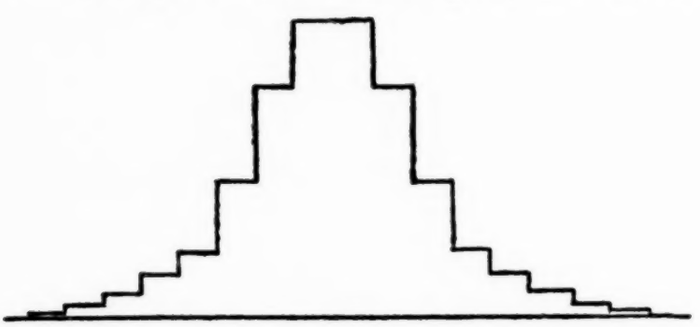


FIG. 2.

such a distribution plus a considerable number of large downward displacements.

The evidence is as follows:

Twenty gifted children, of age about ten, took fifteen forms (A, B, C, etc., in that order) of Part I of the Thorndike Examination, one each school day.[1] The practice effect was practically nil from the third trial on, so the last thirteen trials were used.[2] Differences in difficulty of the different

[1] For these data I am indebted to Dr. H. Race.

[2] Occasionally a pupil missed a trial by reason of absence.

forms of the test were allowed for. Each score was expressed as a plus or minus deviation from the median score of the individual concerned. The results are shown below. The results for any one individual do not differ from the general picture more than would be expected by chance.

TABLE I

VARIABILITY OF AN INDIVIDUAL FROM HIS MEDIAN. GIFTED CHILDREN IN 13 TRIALS WITH A 30-MINUTE INTELLIGENCE TEST

Deviations	Frequency	Frequency Grouping by Steps of 9
− 14, − 15, and − 16	1	1
− 11, − 12, and − 13	6	
− 8, − 9, and − 10	21	48
− 5, − 6, and − 7	21	
− 2, − 3, and − 4	43	
− 1, 0, and + 1	60	128
+ 2, + 3, and + 4	25	
+ 5, + 6, and + 7	39	
+ 8, + 9, and + 10	25	72
+ 11, + 12, and + 13	8	
+ 14, + 15, and + 16	4	4
and at + 29	1	1

From 15 to 20 children in each of grades 3 to 6 (72 in all) were tested at intervals, each with seven forms of the Thorndike-McCall Test in Paragraph Reading.[1] There was no

TABLE II

VARIABILITY OF AN INDIVIDUAL FROM HIS MEDIAN. SCHOOL PUPILS WITH A 30-MINUTE READING TEST.

Deviations	Frequencies					
	Gr. 3	Gr. 4	Gr. 5	Gr. 6	Total	Total Grouping by Steps of 9
− 17, − 18, − 19	.....	.....	.....	1	1	2
− 14, − 15, − 16	.....	.....	.....	1	1	
− 11, − 12, − 13	.....	1	.....	2	3	
− 8, − 9, − 10	.....	3	4	4	11	55
− 5, − 6, − 7	7	13	12	9	41	
− 2, − 3, − 4	23	24	21	26	94	
− 1, − 0, + 1	43	53	50	47	193	391
+ 2, + 3, + 4	28	28	27	21	104	
+ 5, + 6, + 7	3	11	9	9	32	
+ 8, + 9, + 10	1	6	9	2	18	53
+ 11, + 12, + 13	.....	1	.....	2	3	
+ 14, + 15, + 16	.....	.....	1	2	3	3

[1] For these data I am indebted to Dr. A. I. Gates.

appreciable practice effect. The forms are of approximately equal difficulty. Each individual's scores were expressed as plus or minus deviations from his median score. The results are shown below.

About 1400 pupils in the first year of high school (*i.e.*, grade 9) were tested in the early fall, mid-winter and late spring with forms 2, 8 and 4 respectively of this same test. There was a certain improvement due to growth or practice or both, but this was very small in comparison with the difference between trials regardless of practice, and the results are arranged here in such a manner that this improvement does not interfere with the variations with which we are concerned. For each individual the median was found and the other two scores were expressed as deviations therefrom. (The zero deviation of the median from itself was not used.) The cases were collated according to whether the median was the first trial's score, the second trial's score or the third trial's score, and according to the magnitude of the median score. Table III.

The deviations from the very low medians and from the very high medians may now be omitted from consideration because they include so many cases where the median of their trials is by chance far below or far above the true median for the individual concerned. The former make large plus deviations too common, the latter make large minus deviations too common. Table IV.

So far we have measured deviations in the units of the tests, leaving the reader to take it for granted that 10 points up from one of the median points equals 10 points down. If this were not so, and if there were a progressive inequality of the units such that, for example, in the reading scores in reality 40 to 45 = 45 to 52 = 52 to 61 = 61 to 72 = 72 to 85, the apparent symmetry might conceal a real skewness. We do not of course know that the steps of the Thorndike Part I from 80 to 130 (where the scores here reported lie) are all exactly equal, but there is no reason to believe that the ostensible units have smaller and smaller real values as we go up from 80 to 130. The reading test scores used (the T scores

of McCall) also are, from all that is known about them, rather more likely to need swelling than shrinking as we pass from low to high, though they are not likely to need much of either.

TABLE III

VARIABILITY OF AN INDIVIDUAL. DEVIATIONS UP AND DOWN FROM HIS MEDIAN. NINTH GRADE PUPILS IN THREE TRIALS WITH A 30-MINUTE READING TEST

	Median 51 or under				Median 52 to 59				Median 60 to 69				Median 70 or over				Grand Total
	Med. First Trial	Med. Second Trial	Med. Third Trial	Total	Med. First Trial	Med. Second Trial	Med. Third Trial	Total	Med. First Trial	Med. Second Trial	Med. Third Trial	Total	Med. First Trial	Med. Second Trial	Med. Third Trial	Total	
− 23 to − 25	...	...	...	...	...	...	...	...	...	...	...	...	...	1	...	1	1
− 20 to − 22	...	...	...	...	...	...	...	...	...	...	...	...	...	1	1	2	2
− 17 to − 19	...	...	...	...	...	...	...	...	...	...	4	4	...	1	2	3	7
− 14 to − 16	...	...	...	...	1	...	1	2	1	3	1	5	1	4	3	8	15
− 11 to − 13	...	...	1	1	3	3	2	8	3	12	10	25	1	4	7	12	46
− 8 to − 10	...	...	...	...	1	11	1	13	7	22	28	57	1	7	4	12	82
− 5 to − 7	5	3	5	13	18	13	22	53	20	47	34	101	4	6	7	17	184
− 2 to − 4	6	7	3	13	23	32	26	81	38	31	28	97	...	3	2	5	196
− 1, 0, + 1	7	10	5	22	50	44	49	143	57	61	56	174	3	14	16	33	372
+ 2 to + 4	5	5	8	18	16	24	28	68	38	67	51	156	6	8	9	23	265
+ 5 to + 7	3	5	2	10	20	26	19	65	29	30	23	82	...	2	4	6	163
+ 8 to + 10	1	3	...	4	13	5	1	19	6	17	18	41	...	3	1	4	68
+ 11 to + 13	1	2	2	5	7	2	3	12	5	6	7	18	...	2	...	2	37
+ 14 to + 16	2	...	...	2	2	...	...	2	1	...	...	1	...	...	1	1	6
+ 17 to + 19	...	...	...	...	...	...	...	...	...	3	...	3	...	...	...	...	3
+ 20 to + 22	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
+ 23 to + 25	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
+ 26 to + 28	...	...	...	...	...	...	...	...	...	1	...	1	...	...	...	...	1

The same cannot be said of the Army Alpha scores which we have to present. These are in the main between 140 and 205, and there is some evidence, not decisive however, that the step from 140 to 150 is a larger difference in real achievement than the step from 150 to 160, and that this in turn exceeds the step from 160 to 170. On the other hand, the step from 200 to 210 may well be really greater that than from 190 to 200, and the step from 190 to 200 may well be greater than that from 180 to 190.

The first data are the records of 39 college students each with three trials of Alpha given by Richardson and Robinson ['21, p. 302]. I have added 10 to each first-trial score and one to each second-trial score as a rough adjustment for practice effect combined with the inequalities of the three forms of Alpha that were used. (The averages for the three trials were 161.00, 170.51 and 171.54.)[1] The two deviations from the median, omitting the zero deviation of the median case from itself were obtained for each individual. They are shown below.

TABLE IV

THE DATA OF TABLE III, AFTER OMITTING EXTREME LOW AND HIGH MEDIANS

	Omitting the 88 Lowest and 129 Highest Medians		Omitting the 162 Lowest and 129 Highest Medians	
	Steps of 3	Steps of 9	Steps of 3	Steps of 9
− 17 to − 19	4	11	4	11
− 14 to − 16	7		7	
− 11 to − 13	33		30	
− 8 to − 10	70	257	70	242
− 5 to − 7	154		142	
− 2 to − 4	178		166	
− 1, 0, + 1	317	719	300	680
+ 2 to + 4	224		214	
+ 5 to + 7	147		137	
+ 8 to + 10	60	237	53	218
+ 11 to + 13	30		28	
+ 14 to + 16	3		2	
+ 17 to + 19	3	6	3	5
+ 20 to + 22				
+ 23 to + 25				
+ 26 to + 28	1	1	1	1

The other data are the scores of 44 college students each with four trials of Alpha, given in graphic form by Dunlap and Snyder ['20, p. 397]. The first trial was not used because of the very great and irregular practice gain from it to the later trials. The other three were equalized as to practice effect and difficulty of forms by adding 5 to each second

[1] In the records obtained by Richardson and Robinson with Army Alpha used here there is one factor which may work to produce a spurious excess of extreme downward deviations. This is the tendency of certain individuals to be especially slow and cautious in the first trial with the test. Such individuals spend much of the time of the first trial simply in adapting themselves to the test. A general practice correction will not allow for such cases adequately.

trial and subtracting 4 from each third trial.[1] The median of these corrected scores was found for each individual, and then the two deviations from this median (omitting the zero deviation of the median from itself). The distribution of these plus and minus deviations is shown below.

TABLE V

THE VARIABILITY OF AN INDIVIDUAL. DEVIATIONS UP AND DOWN FROM HIS MEDIAN. COLLEGE STUDENTS IN THREE TRIALS WITH ARMY ALPHA

Deviations	Frequencies			Total Grouping by Nine Points
	Richardson Robinson	Dunlap Snyder	Total	
− 20, − 21, − 22		1	1	
− 17, − 18, − 19	1		1	7
− 14, − 15, − 16	4	1	5	
− 11, − 12, − 13	2	3	5	
− 8, − 9, − 10	7	6	13	40
− 5, − 6, − 7	8	14	22	
− 2, − 3, − 4	14	13	27	
− 1, 0, + 1	10	11	21	67
+ 2, + 3, + 4	8	11	19	
+ 5, + 6, + 7	14	9	23	
+ 8, + 9, + 10	4	12	16	43
+ 11, + 12, + 13	3	1	4	
+ 14, + 15, + 16	2	1	3	
+ 17, + 18, + 19		1	1	4
+ 20, + 21, + 22				
+ 23, + 24, + 25				
+ 26, + 27, + 28		2	2	2

The only one of our five experiments where an excess of very large deviations downward occurs is in the ninth-grade trials with the reading test, and the excess here occurs only in about one out of two hundred individuals. A demonstrable excess range downward does not appear. For individuals in such a condition that they attend classes, an excess of very large downward deviations is thus very, very rare.

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[1] The averages for trials 2, 3 and 4 were approximately 165, 174 and 170.